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Foreword

Special Issue "Multipurpose Forest Management" IUFRO Conference on Multipurpose Forest Management: Strategies for Sustainability in a Climate Change Era

Organizing Committee of the International Conference on Multipurpose Forest Management

This special issue comprises 29 papers based on presentations at the International Conference on Multipurpose Forest Management held 20 - 25 September 2009 at *Toki Messe* in Niigata, Japan. The objective of this conference was to explore strategies and techniques for sustainably managing multi-functional forests in an era of climate change. The conference was attended by 113 participants. Five keynote addresses, 25 oral presentations, and 45 poster presentations were made during the conference. Discussion tracks included state-of-the-art techniques and practices for sustainably managing forest resources, enhancing the various functions of forests, and maintaining forest ecosystems. Through reports and discussions, the following recommendations were made at the close of the meeting.

1. In multipurpose forest management, integration of various research areas including socio-economics, earth science and environmental science is needed to overcome currently emerging issues in this era of climate change. These are carbon cycle projection through forest management; consideration of climatic, topographic and human disturbances; biodiversity preservation and forest health; reduction of insect and disease outbreaks, drought, windthrow, and wildfires; processes of participation for all stakeholders; provision of local and international indicators for multipurpose forest management; and accumulation of traditional knowledge on forest resource utilization.
2. Recent advances in statistical and technological tools should be constantly kept in mind, especially in the fields of forest growth modeling, simulation techniques, zoning technologies, spatial analysis, and image analysis.

Review

Forest Management in a Climate Change Era: Options for Planning

Pete Bettinger*

ABSTRACT

Changes in the world's climate may alter the state of forests across broad areas, through changes in tree species composition, tree productivity rates, and natural disturbance regimes. These potential changes may also have a cascading effect on associated environmental services, such water yield, wildlife habitat composition, and biodiversity. The location, extent, and magnitude of potential changes to the climate will vary according to current regional climatic conditions. For example, RAVINDRANATH *et al.* (2006) suggest that some areas of India will become wetter and warmer under one 100-year climate change scenario. This paper examines the issues facing forest planners in an era of climate change, and illustrates the challenges and opportunities for assessing climate change scenarios in forest planning efforts. For example, accounting for tree species physiology in forest planning would allow analysts to recognize that some tree species may be less able to adapt to changing conditions. And, adding socio-economic change projections (development and recreational opportunities) to the analysis of policies will further help one understand the potential impact of climate on biodiversity. These and other additional aspects of quantitative forest planning will enable land managers and decision-makers to think through the vulnerability of forests to changes in temperature, precipitation, and wind speed. In addition, forest plans may need to consider actions that will reduce forest fragmentation, conserve biologically important resources, and reduce the vulnerability of forests to the risks presented along with an assessment of traditional forestry concerns (sustainability of timber production, sustainability of multiple uses, and sustainability of ecosystems). Thus there seems to be a need to assess broad-scale forest management scenarios that minimize adverse impacts and vulnerability to the uncertainties associated with insect, disease, drought, windthrow, and wildfire. This type of planning process would need to account for changes in climatic variables and associated changes in disturbance regimes, and recognize that some forests may be more vulnerable during the adjustment period.

Keywords: forest planning, carbon sequestration, natural disturbances, growth and yield, insect and disease

INTRODUCTION

Over a quarter-century ago WILSON (1981) suggested that the consequences of global warming would be uncertain, but the potential for severe impacts would be significant. Increasing temperatures may lead to regionally-altered wind and rainfall patterns, which could result in shifts of land suitable for agricultural and forestry purposes. WILSON (1981) also suggested that planning and decision-making needed to be proactive to ensure a sustainable lifestyle for the ever-growing human population, yet he recognized that these issues are generally avoided in management planning ("managers are managing .... and planners are planning"). Changes to the earth's climate may alter both the environment in which trees grow, and the subsequent growth of forests (LINDNER *et al.*, 1997). As a result, DYER (1994), among others, encouraged land-use planners to incorporate climate warming considerations into long-range planning efforts. A large number of approaches have been suggested for accommodating the development of sustainable forest plans, and given advances in computer technology, computer software, and data acquisition and management

Corresponding author: Pete Bettinger
E-mail: pbettinger@warnell.uga.edu
* School of Forestry and Natural Resources
University of Georgia
Athens, GA 30602 USA

processes, planning efforts can become quite a complex endeavor (MITCHELL *et al.*, 2004). At the extreme, planning models could be considered multi-objective and dynamic, with feedback mechanisms and system interactions that address a fuzzy decision environment. As INNES *et al.*, (2009) suggest, management planning will evolve as new stresses and threats affect forestlands, and new management strategies will likely be developed to take advantage of the opportunities posed by a changing climate. However most current forest plans are developed in a rather deterministic manner (HUANG *et al.*, 1998).

The level of sensitivity of forest management goals to potential climate changes will be a function of the current and future forest landscape pattern, the temporal and spatial impacts of climate changes, and the specific effects of these changes on forest trees (BLATE *et al.*, 2009). The problem in forest planning with regard to potential changes in the climate is best described by BINKLEY and VAN KOOTEN (1994), who suggest that three systems need to be integrated: climate, terrestrial, and forest sector. Current estimates of climate change suggest that the changes may be too rapid for some forests to naturally maintain or adjust their structure, function, and composition (Bosworth *et al.*, 2008), thus some sort of management intervention may be necessary. The probable effects include increased warming at higher latitudes of the northern hemisphere, and decreased precipitation and soil moisture patterns in the middle latitudes, along with an increased frequency of dry years (TURNER and ROMME, 1994). These conditions can lead to changes in the frequency of natural disturbances, since wildfire (for example) potential is related to fuel moisture, precipitation, and humidity conditions. The increase in vulnerability of forests world-wide is therefore related to the spatial distribution of forested areas, projections of spring and summer temperatures, and projections of water availability (WESTERLING *et al.*, 2006).

Revenue generated from planned timber harvests can potentially support the forest management activities necessary to address alterations in the timing, frequency, and intensity of natural disturbances due to climate changes (GÄRTNER *et al.*, 2008). As a result, planners may be asked to take historical and projected changes in the climate into consideration when developing long-term forest management plans (BOSWORTH *et al.*, 2008). For this review, a comprehensive literature search was performed to understand the current opinion of experts around the world as it relates to the actions necessary for land management planners to account for, and develop management responses to, potential changes in the world's climate. This review is focused not on the evolving philosophies of sustainable forest management or adaptive management, which guide many of the strategies that have been proposed to address potential changes to the climate, but on the specific actions planners can take to address the concerns of an evolving set of needs of land managers and decision-makers.

DISCUSSION

The literature concerning the potential impacts of changes in climate on forest resources is extensive. Most of the research centers on the use of general circulation models and their predictions of climate changes and the resulting vegetation patterns. This paper was designed to categorize the opinions of researchers, along with their recommendations, into suitable themes that relate directly to forest management planning processes. As a result, the discussion that follows concentrates on shifts in land use, changes in vegetation patterns, natural disturbances, growth and yield modeling, the scale of planning, carbon sequestration, invasive species management, and the acknowledgement of uncertainty in planning models. After a brief description of the potential issues that may arise for each of these topics, some specific issues regarding the recognition of these issues in forest plans are highlighted. In contrast to much of the published literature, which generally promotes changes in management philosophy given projected changes in the climate, this discussion identifies the challenges facing planners to address the concerns of land managers and decision-makers who desire to see potential changes to the climate acknowledged in forest plans.

Shifts in Land Use

Land management planning generally begins with an assessment of land classes and their suitability for accommodating a wide variety of forest-based uses (BETTINGER *et al.*, 2009). These determinations are usually made once, at the beginning of the planning effort, and are usually considered fixed throughout the temporal extent of the time horizon under consideration. However, under many climate change scenarios, agricultural and forest uses of the land will likely shift as areas become more (or less) capable of producing crops in an economically efficient manner. Significant changes in the prices for agricultural and forest products could also influence land use distribution (HODGES *et al.*, 1992). And, changes in markets, trade, prices, and non-timber resource values may further affect land tenure in some areas of the world undergoing climate changes (BINKLEY and VAN KOOTEN, 1994). Although policies differ on private and public lands, there is a need to assess the tree species used for widespread planting efforts in reaction to climate change, and to prohibit the distribution of exotic tree and plant species that may cause problems in the future (THORPE *et al.*, 2006). Unfortunately, the gridlock created by human development of land, as expressed through land use changes, forest fragmentation, and public desires, has never before affected the natural evolution of tree species range distributions (BOSWORTH *et al.*, 2008). In addition to changes in suitable land uses, forest roads may need to be evaluated and perhaps re-designed to withstand changes in rainfall intensity and erosion events (BLATE *et al.*, 2009). As a result, the following items are suggested for consideration in the development of

forest plans.

- For long-range planning efforts there seems to be a need to develop evolving land classification and use projections that take into account changes in climatic variables and their effect on natural forest distribution and composition.
- Similarly, human developmental pressures should be projected and incorporated into forest plans to assess management options and resource vulnerability.
- Forest road systems need to be assessed for their ability to provide access over time to resources of interest, and for their contribution to resource degradation in response to shifts in precipitation patterns.

Shifts in Natural Vegetation Patterns

Predictions regarding shifts in the natural range of vegetation are typically based on models that were developed from correlations between the conditions of sites that were occupied by certain tree species, and the conditions of sites that were not, and these projections thus assume that climate is the major factor in determining future natural ranges of vegetation (Carmel and Flather, 2006). As a result, the potential impacts of changes in the climate on forest distribution and forest health would obviously affect forest management decisions, and therefore adversely affect some (if not all) forest-based economies (Hodges *et al.*, 1992). Historically, plant and animal species have both shifted their natural ranges due to climatic changes; the retreat of glaciers and subsequent colonization by tree species is but one example of new patterns of vegetation were created after changes in the climate (Bosworth *et al.*, 2008). Water stress is partly responsible for vegetation pattern shifts, although local temperatures and nutrient availability are factors as well (Martin, 1996). Simply put, potential changes to the climate may affect the suitability of land to support vegetation (Huang *et al.*, 1998). The effect of these changes will likely affect natural disturbance frequency, intensity, and duration as well. Turner and Romme (1994) proposed that the vegetation that naturally regenerates in areas of large and severe wildfires may gradually be different in composition than the plant communities that were present before fires. However, some have suggested that the current pattern of vegetation on the landscape could provide a useful indication of future vegetative and landscape mosaic trends in the event of a changes in natural disturbances under a changing climate (Turner and Romme, 1994).

The dispersal mechanisms of trees and the interactions among tree species need to be taken into account with changes in the climate (Davis *et al.*, 1998). Therefore, changing climate conditions may represent a threat to biodiversity, as tree species may be required to disperse through fragmented landscapes in order to keep pace with conditions favorable to their existence (Pearson and Dawson, 2005). Further, the natural range limits of a number of tree species may shift dramatically under a warming climate scenario, and therefore the ability of tree species to naturally migrate is a concern (Dyer, 1994). Tree species with small natural geographical ranges may be the most vulnerable (Schwartz *et al.*, 2006), and under the worst-case scenario that Lindner *et al.* (1997) examined, none of the forest tree species that are currently present in one region of the world (Germany) could thrive in certain areas of the landscape.

Managing for forest complexity is likely to result in a landscape with greater resilience toward changes in climate (Crow, 2008). However, additional information on the potential shifts in vegetative patterns as a result of climate change is needed, since some (e.g., Clark, 1998) have proposed that some plant species may be able to migrate naturally at rates faster than those predicted from average dispersal distances. The value of management actions aimed at adapting to climate change should be considered, since attempting to maintain the existing ecosystem components may not be adequate, thus intensive management actions that are designed to deliberately shift the range of tree species to newly-formed suitable habitat may be necessary (Thorpe *et al.*, 2006). Planning for natural corridors to facilitate tree species migration has also been suggested (Blate *et al.*, 2009), however, natural corridors that are designed for migration of plants through seed dispersal processes may not be effective, since migration may not keep pace with the projected change in climate (Pearson and Dawson, 2005). Others suggest that a landscape composed of many small patches within a few larger patches will best serve to connect various ecosystem functions and facilitate the flow of materials and organisms across the landscape (Crow, 2008).

The argument for these assessments is centered on our attempt to assist the evolution of forested environments toward a new equilibrium that can once again thrive without a continued series of management actions (Thorpe *et al.*, 2006). Further, since successional dynamics of natural areas will likely change (Blate *et al.*, 2009), there will be a need to organize and carefully consider the potential impact of these dynamics on planning processes that include state-transition modeling components, since management actions that would assist the transition and adaptation of forests would seem appropriate under some circumstances (Millar *et al.*, 2007). Artificial regeneration of tree species on the edges of, or outside, their natural range may be important in assisting with the migration process (Nitschke and Innes, 2008), thus as noted earlier, flexibility in the land classification and allocation processes would seem necessary to account for these types of transitions across the landscape. However, trees need to be of proper genetic characteristics for the climate in which they are established (Crookston *et al.*, 2008). In sum, in response to shifts in the natural range of vegetation may require planners to:

- Examine alternatives for managing forest resources in a manner (spatially and temporally) that may facilitate the migration of tree species (naturally regenerated and planted)

and toward conditions to which they might become adapted (PEARSON and DAWSON, 2005).

- Plan for natural corridors for tree species migration (BLATE *et al.*, 2009).
- Develop alternative transitional pathways for forest management regimes that take into account the notion that trees will be stressed along the boundaries of their shifting natural ranges.

Natural Disturbances and Disturbance Processes

Changes in climate may have an effect on the frequency, intensity, and range of disturbance events such as wildfires, insect outbreaks, and the spread of disease (HUANG *et al.*, 1998; YANCHUK and ALLARD, 2009). A number of research studies suggest that increases in the probability of catastrophic losses from these events are likely. BLATE *et al.* (2009) also suggest that there will be a shift in hydrologic processes due to changes in precipitation timing and intensity, and due to the threat of drought in some areas. Therefore, changes in climate may also affect water resources that depend on precipitation levels, and hence affect water yields (SUN *et al.*, 2009; WANG *et al.*, 2008). As a result, if future climatic conditions are assumed to be different than past conditions, natural disturbance rates would likely change, and the condition of the landscape and capability of forests to produce desired outcomes will then likely change. In response to these potential effects, planners could adjust disturbance parameters of interest (frequency, intensity, size, and duration of disturbances recognized) over the time horizon of a forest plan to reflect the potential changes (CAMPBELL and DEWHURST, 2007).

Forest growing seasons will likely be affected under current scenarios as they generally lengthen, and hotter, drier conditions may result in increases in insect and disease mortality rates (BOSWORTH *et al.*, 2008; BLATE *et al.*, 2009). Therefore, potential changes in the climate will likely have an impact on the frequency, intensity, and scope of insect and disease outbreaks. For example, with increased temperatures in higher latitudes, SIEBEN *et al.* (1997) suggest that there will be sufficient growing season heat to facilitate the expansion of the range of the white pine weevil (*Pissodes strobi*) northward and upward in elevation. Commercial thinning is widely seen as a way to control insect outbreaks through adjustments in stand density and alterations of the growing environment, however thinning without fuel management actions may be counterproductive because fire risk may increase given additional fuel loads on the ground. This issue is complex, since key wildlife habitat characteristics, such as snags and down logs, may also be viewed as fuel components, and may need to be maintained on the landscape in order to conserve habitat quality for plant and animal species that require these components (NITSCHKE and INNES, 2008).

The changes in the frequency, intensity, and scope of wildfires will vary according to the spatial juxtaposition of forest resources in relation to potential changes to precipitation and air temperature patterns. In western Canada for example, fire danger is projected to increase given associated increases in summer temperatures (KADONAGA, 1997). Altered fire regimes have already been detected for a number of areas in North America, with human-induced climate change is suggested as one of the causes (GILLETT *et al.*, 2004; BLATE *et al.*, 2009). In planning efforts, HARTLEY and MARSHALL (1997) developed an iterative updating procedure where for each decade within a forest plan, climate conditions were predicted, wildfire and natural mortality were assumed based on probabilities of these occurring, and alternative regeneration pathways were developed for disturbed areas. As noted earlier in relation to insect and disease concerns, one adaptation option for restoring and enhancing forests is to reduce fuel loads, and increase the use of prescribed fire (BLATE *et al.*, 2009). Low-severity prescribed fire has been shown to be effective in reducing the risk high-severity wildfires, drought susceptibility, and insect and disease outbreaks (BLATE *et al.*, 2009). In this sense, prescribed fire can be used to enhance the resilience of a forested area. Unfortunately, fuels reduction treatments act to reduce carbon stocks in forests, although some of the captured woody biomass may sequester carbon in the resulting forest products. However, forest fuel management treatments can also be considered as a way to mitigate the potential emission of carbon into the atmosphere through wildfire (BOSWORTH *et al.*, 2008).

Planning processes that recognize relationships between forests and water yield should also consider the uncertainties in water supplies that may be encountered under a changing climate, particularly in areas with growing human populations that are dependent on natural sources of water for general public use (SUN *et al.*, 2008). BETTINGER *et al.* (2007) described three general processes of increasing complexity that planners might use to integrate water yield concerns into forest plans, from the general use of deterministic water yield coefficients to the sophisticated integration of complex water yield models and forest planning processes. In response to each of these concerns, planners should consider the following:

- Incorporating into planning efforts models that take into account the frequency, intensity, size, and duration of natural disturbances.
- Recognizing that alternative forest management prescriptions may be necessary to control fuel loads and to provide environmental services that result in habitat characteristics suitable for forest-dwelling wildlife.
- Understanding and recognizing through management regimes the interaction between fuels management treatments (which can act to mitigate the emission of carbon into the atmosphere) and prescribed fire treatments (which can act to emit carbon into the atmosphere), and how these can be used together to reduce the impacts of wildfire, insect, and disease issues that may arise with changes to the climate.

- Incorporating more closely water yield models with forest planning efforts.

Growth and Yield Modeling

The suggested changes in the climate (namely precipitation and temperature), if realized, will affect the quality of forest-growing sites, and with proposed shifts northward in the range of some tree species, yields of wood products in the southern-most areas are projected to decline (HODGES *et al.*, 1992). The projection of forest inventory characteristics through time, assuming changes in climate, will require that relationships be developed between the forest inventory and climate variables such as temperature and precipitation (HARTLEY and MARSHALL, 1997). Therefore, modification of growth, mortality, and regeneration processes in forest growth and yield models have been proposed, since increases in temperatures and changes to hydrologic cycles will likely stress these relationships (CROOKSTON *et al.*, 2008). Our ability to make reliable estimates of growth responses to climate change, however, may be limited by our understanding of the interaction between atmospheric CO_2 and the changes in temperatures (EAMUS, 1996).

Operationally, a considerable amount of effort has been expended on developing disease-resistant genotypes of major commercial forest tree species, and this becomes even more critical given the uncertain effects changes in the climate may have on insect and disease issues (YANCHUK and ALLARD, 2009). Since artificial migration of forests has been proposed to facilitate shifts in vegetation patterns, planners should keep in mind that the knowledge gained from previous empirical research may not be transferable to tree species that have been established outside of their current natural range (YANCHUK and ALLARD, 2009). As a result, controlled planting trials, accompanied by monitoring and evaluation processes, should precede widespread planting of tree species outside their current ranges (THORPE *et al.*, 2006). Genetic guidelines for reforestation should also be periodically reviewed (BLATE *et al.*, 2009).

In general, warmer areas of the world may see an increase in the net primary production of forests (RAY, 2008), however the effects will vary regionally. For example, under some modeling scenarios, net primary productivity and could be reduced, and water yield increased (due to lower leaf areas) in the present range of loblolly pine (*Pinus taeda*) in the southern United States (MCNULTY *et al.*, 1996). In other areas, such as the northern United States, and under other scenarios, net primary productivity and could be increased and water yield decreased (ABER *et al.*, 1995). In sum, the direction and magnitude of the impact of climate change on net primary production is largely dependent on the degree of warming and the associated impacts on precipitation (CHIANG *et al.*, 2008). In most areas of the world, the effects of climate change on the growth of forests will also arise from changes in the normal growing season length (longer or shorter), and perhaps suggest that a fertilization effect on forests from additional carbon dioxide should be considered (HUANG *et al.*, 1998). However, while an increase in carbon in the atmosphere may provide a fertilization effect, the development of soil conditions, particularly at higher elevations, may progress at a rate slower than necessary (BOSWORTH *et al.*, 2008). Forest growth may also increase where soil conditions are suitable for the retention of increased precipitation, along with the positive feedback from carbon and nitrogen cycles that amplify the responses (PASTOR and POST, 1988). For example, MONSERUD *et al.* (2008) suggest that the site index for lodgepole pine in Alberta (Canada) will increase by about 1 meter per year, although the range of lodgepole pine may eventually shift due to changes in precipitation levels. Others have noted that while elevated atmospheric carbon levels may enhance near-term forest growth in areas where water and nitrogen are not in short supply, other industrial pollutants (in addition to climate stress) may actually decrease forest growth in the longer term (BLATE *et al.*, 2009). Many currently available empirical forest growth and yield models assume that future growing conditions will be similar to recent past growing conditions and the interaction of these with natural regeneration, ingrowth, mortality, and species-interaction processes. Process-based growth and yield models, however, may provide a framework within which one can estimate forest growth responses to a changing climate (GARCIA-GONZALO *et al.*, 2008).

Currently, there is a scarcity of data on the long-term dynamics of forest tree species under a warming climate (LINDNER *et al.*, 1997). Given the large uncertainties involved, the best one might do at present is to make probabilistic estimates of climate change effects on forest growth (e.g., WOODBURY *et al.*, 1998). These efforts might inform us of the chances that growth and yield of forest products may increase or decline under certain scenarios. One option for forest adaptation that would address the sustainability of forests is for planners and managers to develop alternative silvicultural regimes that are designed to reduce drought stress in trees (BLATE *et al.*, 2009). The selection of tree planting stock and planting methods should also be considered carefully in a long-term forest management plan (BOSWORTH *et al.*, 2008). As a result of these findings, planners should consider the following:

- Adjusting growth rates, mortality, ingrowth, and regeneration assumptions in the growth and yield models that are used to provide the forest management regime data (e.g., potential tree volume over time) necessary for forest planning efforts.
- Considering alternative growth and yield models that account for the interaction of water stress, carbon availability, and subsequent growth responses that are not readily evident in empirical growth and yield models.

Scale of Planning Efforts

The time frame that forest plans cover varies from relatively short (a decade or two) for organizations with a commodity production or economic focus, to relatively long (a century or more) for publicly-managed land management organizations that have broader ecological and social objectives. It is highly unlikely that land management organizations with short planning horizons would address potential changes in the climate through their forest plans. However, if the sustainability of forest resources over the long-run were of interest, longer-term forest plans would seem to be the appropriate venue for accommodating risk and uncertainty related to climatic variables. As one may be aware, local management decisions should be made within the context of the ownership, the landscape, and regional and higher hierarchies, since focusing on a single scale in time or space may obscure processes that are important at larger scales (Crow, 2008). For long-range planning purposes, regional sensitivity of plant species to climate changes and analyses of associated risks need to be evaluated at a scale larger than the administrative boundaries of a landowner (Lindner *et al.*, 1997). Unfortunately, the data and time available for appropriately recognizing resource conditions outside of an ownership boundary is generally lacking, thus most forest planning efforts today focus on the objectives, goals, and impacts within confined spaces. However, while the spatial resolution of climate change projections is generally inconsistent with typical forest planning management units, the effects can be disaggregated down to the management unit scale (Ray, 2008) if these are desired. As a result, planners who are directed to consider sustainability of forest resources over a long time frame should consider:

- Developing a model that can estimate impacts and disturbance agents beyond the scope of their ownership boundary.
- Developing methods for disaggregating broad-scale estimates of changes to precipitation and temperature patterns down to the local scale inherent in the planning effort.

Carbon Sequestration

One recent challenge for some forest planners has been to balance commodity production (or economic) goals with specific carbon sequestration goals (Krcmar *et al.*, 2001; Garcia-Gonzalo *et al.*, 2008). Carbon can be considered sequestered in the above-ground stem of trees, in the below-ground root systems, and in the soil of forests. In terms of land management options, some have suggested that short-rotation woody biomass plantations would be of value in sequestering atmospheric carbon, while also providing an alternative energy source (Bosworth *et al.*, 2008). Unfortunately, short-rotation forestry is not appropriate in many areas of the world, given the objectives of various land ownerships. Further, when managing older forests and forests represented by uneven-aged management regimes, tree mortality releases back into the atmosphere some of the carbon that had been sequestered. Carbon sequestration is also interrelated with wildfire risk, since increases in wildfire frequency may result in changes to forest composition and tree density levels, both of which will ultimately affect carbon pools (Westerling *et al.*, 2006). As a result of uncertainties in timber yields (due to a changing temperature and precipitation regimes and CO_2 fertilization effects), and imprecise information on carbon sinks as they relate to the life cycle of carbon in wood and wood products, there is some uncertainty involved in estimating and projecting carbon flows associated with forest management (Krcmar *et al.*, 2001). Alternative scenarios are currently used by many land managers during the planning process to help understand these management uncertainties, and Krcmar *et al.* (2001) suggest that these techniques may be of value in understanding the potential effects of climate change on carbon sequestration options. In rather complex forest planning processes, carbon could be modeled as a flux, by accounting for changes in the level stored above-ground as biomass and biomass growth, changes in harvest levels, changes in below-ground storage, and the associated dynamics of carbon stored in products and ultimately released through decay and other processes (Krcmar *et al.*, 2001). In sum, planners could do the following to recognize the impacts of climate change on carbon sequestered in forests:

- Incorporate methods for estimating the level of carbon sequestered in various forest types and how these stocks will change over time with management activities and potential changes to the climate.
- Develop methods to account for uncertainty in carbon stocks, and analyze the sensitivity of forest management objectives to various levels of uncertainty.

Invasive Species Management

The opportunities for establishment and distribution of invasive plant species are expected to increase with changes in the climate, and the area potentially affected will pose a problem for land management planners (Bardsley and Edwards-Jones, 2007; Bosworth *et al.*, 2008). Increases in atmospheric carbon may be partly responsible for the spread of invasive plants (Bosworth *et al.*, 2008), and the spread of exotic species and diseases may involve multiple scales of interacting environmental factors (Crowl *et al.*, 2008). Additional information may be required to adequately assess the drivers of invasive species range changes over space and time, and in relation to climate change and human management of the landscape (Crowl *et al.*, 2008). As a result, taking defensive actions through management at key migration points may help block or remove invasions and increase resistance (Millar *et al.*, 2007). Some have suggested that management plans that incorporate intensive management options may be appropriate

in areas where establishment may enable the retention of desired species (MILLAR *et al.*, 2007). As a result, the following actions could be taken by forest planners to more closely account for invasive species in forest plans:

- Incorporate functional relationships that describe the establishment, growth, and effects of invasive species on forests into forest planning efforts.
- Develop forest management regimes that could act to mitigate the spread of invasive species and the subsequent effects of invasive species on forest growth and forest health.

Acknowledgement of Uncertainty

Many of the previous topics have suggested that uncertainty and risk need to be acknowledged in order to increase the resilience of forests to potential changes in the climate, and to facilitate shifts in vegetation patterns and recognize changes in land use. Unfortunately, and perhaps inherent in the nature of humans, management under uncertainty is often viewed as annoying and confusing, and in many cases of forest planning, uncertainties are ignored in economic and ecological relationships (PAOLI and BASS, 1997). The treatment of uncertainty can be challenging and time-consuming, yet a thorough examination of the uncertainties may change what is regarded as the best course of action for management (PAOLI and BASS, 1997). Some suggest that planning for uncertainty is the best option for forest management, so that risks can be minimized by considering and implementing multiple courses of action (MILLAR *et al.*, 2007). While simulation models and heuristics may be well-suited for modeling uncertainties in forest management planning, linear programming and mixed-integer programming are more widely used today to develop forest plans (BETTINGER *et al.*, 2009). Unfortunately, it is difficult to account for uncertainty in these latter two types of planning models, since it is generally assumed that all technical coefficients would be known with certainty before a planning problem is solved. However, PAPPS (2000) provides an example of incorporating stochastic forest management relationships into linear programming, and a number of others have incorporated stochastic relationships into forest planning processes that recognize natural disturbances (e.g., GASSMANN, 1989; ARMSTRONG, 2004; YANG *et al.*, 2004). As a result, planners should:

- Investigate methods for incorporating stochastic relationships into forest planning models, particularly when the functional relationships within models (whether they are growth and yield models, water yield models, or natural disturbance models) are necessary to more adequately represent the current state of knowledge in these areas.

CONCLUSIONS

Although forest plans are always developed under conditions that contain risk and uncertainty, no matter the length of the planning horizon (BRICEÑO-ELIZONDO *et al.*, 2008), these uncertainties and risks may be ignored, thus bold new forest management strategies have been called for in the management of forests in response to potential changes in the climate (YANCHUK and ALLARD, 2009). HALPIN (1997) further suggested that forest managers must be creative and explore new techniques in management planning to assess the impacts of potential changes in the climate, and went further to suggest that a regional-level view would be more appropriate than a landowner-centric planning process which is typical of most operational planning efforts. Thus the consensus among the recent research is that long-range planning efforts need to incorporate risk and uncertainty into planning efforts to understand where the vulnerabilities exist, where areas of resilience lie, and how tree species shifts will impact overall management objectives (NITSCHKE and INNES, 2008). Unfortunately, risks are difficult to predict given the ecological, economic, and social framework within which they must be couched and the climatic thresholds that may occur and result in irreversible impacts on an ecosystem (NITSCHKE and INNES, 2008). Further, the task of deciding how to judge the significance of these actions, and how to interpret the ecological responses and vulnerabilities, is not perfectly clear, since these decisions and interpretations are made by decision-makers and land managers who must consider other issues outside of the planning system (NITSCHKE and INNES, 2008). In a typical forest planning process alternative forest plans are developed, their consequences are ranked, and values are placed on them in a relatively subjective manner by the decision-makers and land managers (BRICEÑO-ELIZONDO *et al.*, 2008).

The broader implication associated with the suggestions made here is that planners need to develop multiple scenarios that assign risk at different levels, and that these scenarios may be necessary for land managers and decision-makers to more fully understand the sensitivity of forest plan results to the uncertainties that lie ahead (GARCIA-GONZALO *et al.*, 2008). This concern is particularly relevant in planning efforts that seek to incorporate stochastic relationships related to natural disturbances and commodity production goals, thus some have suggested that stochastic planning models (LOHMANDER, 2007) or models that include fuzzy set relationships (BRICEÑO-ELIZONDO *et al.*, 2008) are more appropriate in these instances than more commonly-used deterministic models such as linear programming. In sum, ignoring the potential changes to the landscape that may occur over long periods of time may result in inaccurate estimates of timber production and ecological services (BRICEÑO-ELIZONDO *et al.*, 2008).

Much of the recent research also suggests that management actions must be designed to promote resilience and therefore reduce the risk of natural disturbances; these ap-

proaches have been called at times "climate-smart" (NITSCHKE and INNES, 2008). When considering climate change, forest management plans should address changes in precipitation patterns, fire regimes, tree physiology, and landscape patterns and processes (BLATE *et al.*, 2009). Obviously, value judgements on behalf of land managers and policy-makers will likely be used to assess the advantages and disadvantages of man's attempt to manipulate the environment in response to climate change (THORPE *et al.*, 2006). This is because the information we possess about the effect of climate change on forest resources is not as robust as the information we possess about vegetation dynamics in our current system. However, even if planners were able to account for all of the potential changes in forest ecosystem dynamics at an ownership (or larger) scale, the resulting management problem, when quantified, may become computationally intractable (KRCMAR *et al.*, 2001).

Land use change is a compounding factor in forest planning, since as one plans for shifts in forest composition, changes in land uses need to be estimated along with (perhaps) further fragmentation of the forested landscape. Ecological restoration of forests has been repeatedly called for in response to the increases in wildfire risk, yet actions along these lines may not be sufficient to reverse current trends in wildfire behavior. Decision-support systems such as the one suggested by GÄRTNER *et al.* (2008) can be used to help land managers and decision-makers think through the various options for managing a landscape in light of changes to the climate. And shorter-term land management planning processes that provide flexibility in management activities in order to reduce risks over a single tree rotation period have also been suggested even if these actions do not lead to improvements in forest yields (NITSCHKE and INNES, 2008). In general, a reduction in the stressors that increase the vulnerability of forests (fragmentation, pollution, invasive species, altered fire regimes) has been proposed as a goal for forests to allow them to withstand the impacts of climate change (GLICK *et al.*, 2009). Also proposed as hedges against changes in the climate are the need to build redundancy in forest types, the need to provide reserves of various types of habitat, and the need to maintain connectivity of habitat (HALPIN, 1997). While intensive forest management, as we noted earlier, can help solve some of the problems associated with potential changes to the climate, some have also suggested that uneven-aged forest management may be more appropriate for areas that have both low resilience and low disturbance risk (NITSCHKE and INNES, 2008).

As with any forest planning analysis, the results of alternatives need to be communicated to the decision-makers in a manner that facilitates informed and semi-rational decisions. This is even more important in cases where abstract and uncertain aspects of climate change are factored into management scenarios (DOCKERTY *et al.*, 2006). In addition to the maps and tabular summaries that describe alternative management scenarios, DOCKERTY *et al.* (2006) suggest that digital photo montages that depict somewhat realistically how a landscape will change over time may be of value in helping decision makers consider alternative policies. Perhaps more importantly, there is a need to increase the technical understanding of the issues involved, through the development of educational materials aimed at employees, managers, and other stakeholders (BLATE *et al.*, 2009). Unfortunately for forest planning processes, these suggestions, along with those proposed earlier in this review, will require additional time, cost, and effort on behalf of planners. It remains unclear whether forest management organizations will devote the resources necessary to more fully account for effects beyond ownership boundaries, changes in growth rates, effects on carbon sequestration, natural disturbances (and changes in their timing, intensity, size and duration), and other uncertainties. Public pressure to recognize these concerns may force some organizations to make adjustments to their planning processes, yet the more financially-savvy management organizations will likely balance the cost associated with additional investments in planning processes with estimates of future benefits of having done so. In this latter case, some organizations may decide to forgo many of the suggested changes in quantitative planning processes and consider strategic alternatives in a more qualitative manner.

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Review

Silvicultural Strategies, Sustainability, and Adaptation to Climate Change in Forests of the Atlantic Region of Europe

William L. Mason[*1] and Céline Meredieu[*2]

ABSTRACT

Many forests of the Atlantic region of western Europe are plantations created in the last century after a long history of deforestation. These forests have high growth rates by European standards and support competitive wood using industries. However, in some countries of the region (Scotland, Wales) there is increasing pressure to diversify the forests to meet the requirements of multifunctional forestry, while in other areas (the Landes region of south-west France) recent severe storm damage raises the need to increase the resilience of plantations to future climate change. A range of silvicultural systems can be used to diversify plantation forests, but these will have different impacts on indicators of sustainability. The framework of Forest Management Alternatives (FMAs) developed in the EU Eforwood project spans the range of possible stand manipulation from no intervention in a long-term reserve to complete above-ground biomass removal in short rotation forestry. Using the example of a Sitka spruce stand in Scotland, we present the values of a range of economic, environmental, and social indicators associated with each FMA. Traditional plantation management practices based on planting a single species and patch clear felling are more attractive in economic terms than for ecosystem services. A favoured alternative of combined objective forestry using a range of species and smaller clearfelled areas is not as attractive in economic terms and produces only small gains in ecosystem services. A close-to-nature option produces greater recreational and biodiversity benefits, while being only marginally less economically viable than clearfelling, because the use of natural regeneration saves on restocking costs. Current policies and guidelines for adapting forests to climate change propose greater use of less intensive FMAs at the expense of traditional plantation management and we illustrate possible impacts of such scenarios on selected sustainability indicators. Future development of this framework will need to link growth models with predictions of stand vulnerability to abiotic and biotic risks to allow more rigorous examination of the effects of changes in the balance of FMAs upon sustainability indicators. We outline research challenges which need to be tackled to allow managers to devise and implement appropriate silvicultural strategies to adapt Atlantic forests to climate change.

Keywords: plantation forests, silvicultural systems, sustainability, climate change

INTRODUCTION

The Atlantic region of western Europe covers more than 20 degrees of latitude, stretching from Cape Wrath at the northern end of Scotland (58° 36′ N) to Tarifa (36° N) at the southern tip of Spain. This region contains all of Ireland, the western parts of Great Britain and France, the north-western and south-western provinces of Spain, and all of Portugal. These areas are characterised by an oceanic climate with relatively mild winters, regular rainfall spread by westerly winds, and comparatively long growing seasons. Furthermore, the northern part of the region receives the warming effect of the Gulf Stream which allows genera like *Eucalyptus* spp. to be grown at high lati-

Corresponding author: William L. Mason
E-mail: bill.mason@forestry.gsi.gov.uk
[*1] Forest Research, Northern Research Station, Roslin, Scotland, EH25 9SY, UK
[*2] INRA, UMR1202 BIOGECO, 69 Route d'Arcachon, F-33612 Cestas Cedex, France

tudes (57° N) in western Scotland. The benign climate coupled with varied food supplies available from land and sea resulted in early colonisation by hunter-gatherer bands following the start of the current interglacial some 11,500 years ago (CUNLIFFE, 2001). This was followed by the development of settled human societies by some 5,000 years ago and in the subsequent millennia the ready access to marine transport routes led to considerable trading between the coastal areas of the region which became characterised by common 'Celtic' languages some 3,000 years ago (CUNLIFFE, 2001). Despite many political and social differences over subsequent millennia (e.g. the differential impact of the Roman empire (Perlin, 1989)), the various countries and provinces of the Atlantic seaboard retain a long history of shared experience which was recognised by the European Union in the establishment of the 'Atlantic Arc' region in 1989 (CUNLIFFE, 2001).

The forests of this region have been exploited by humans for thousands of years with evidence of systematic coppice management of broadleaved woodland some 5,000 years ago (RACKHAM, 2006). A consequence of this history was the gradual reduction in forest cover over the centuries leading to the formation of heathland vegetation and scrub woodlands in many parts of the region (e.g. SMOUT, 2003). Thus, in Scotland forest cover in 1900 was about 4% of the land area (MASON, 2007), while the equivalent figure for Ireland was 1% (COILLTE, 2007). In south-west France, by the late 1700s, the reduction of forest cover had been enhanced by burning to facilitate grazing leading to the formation of extensive areas of heath and swamp, while the coastal sand dunes became a threat to inland villages in the absence of protective forests (REED, 1954). From about 1700 onwards, there was increasing recognition of the need to restore forest cover to the degraded landscapes of the region as a means of revitalising impoverished rural economies and to provide greater visual diversity (HOUSE and DINGWALL, 2003). The last two centuries have seen a progressive restoration of forest cover of the region, mainly through the establishment of productive plantation forests. In Portugal, there are about 650,000 ha of eucalyptus plantations, mainly *Eucalyptus globulus* LABILL. (ANON., 2009b), grown on a 12 year pulpwood rotation. In north Spain, plantations of maritime pine (*Pinus pinaster* AIT.) cover about 600,000 ha while those of radiata pine (*Pinus radiata* D. DON.) make up a further 90,000 ha (BALBOA-MURIAS *et al.*, 2006). Further north, the Landes area of France now contains 826,000 ha of even-aged maritime pine forests (IFN, 2009a), while there are extensive plantations of Sitka spruce (*Picea sitchensis* BONG. CARR.) in the British Isles with 528,000 ha in Scotland (FORESTRY COMMISSION, 2008) and 328,000 in Ireland (FOREST SERVICE, 2007). All these plantation forests are highly productive by European standards with increments of 10–24 m^3 ha^{-1} yr^{-1} or more (DUNCKER *et al.*, 2008) and support important wood using industries.

Since the beginning of the 1990s there has been an increasing emphasis throughout the world on the principle of sustainable forest management (SFM) for multiple benefits. European guidelines on SFM were developed at the 1993 Helsinki Ministerial Conference on the Protection of Forests in Europe (MCPFE, 1993) and have been refined through further MCPFE declarations. These guidelines oblige member states of the EU to consider the environmental and social functions of forests as well as the economic returns generated through timber production. Meeting these obligations is arguably more problematic for countries in the Atlantic region because plantation forests managed primarily for timber production are such a major component of the forest resource. For instance, in Ireland and the United Kingdom, plantations make up 90 and 69 per cent respectively of the forest area (FAO, 2001) while in Les Landes almost 50% of all forests are of plantation origin (more than 80% of annual reforestation since 1999; CRPF AQUITAINE, 2009).

For this reason, intensive research has been undertaken to try and understand the ecosystem services provided by plantation forests in the region (e.g. biodiversity – see HUMPHREY *et al.*, 2003; BRIN *et al.*, 2008). In Great Britain, there has been increasing recognition of the benefits provided by appropriate management of native woodland types, such as Caledonian pinewoods of northern Scotland (Mason *et al.*, 2004), and of the desirability of restoring native woodland communities where conifer plantations were established on sites that were previously broadleaved woodland (THOMPSON *et al.*, 2003). This has reflected changes in the forestry policies of the various countries of the United Kingdom where both the Welsh (ANON., 2009a) and the Scottish (ANON., 2006) forestry strategies propose the use of a wider range of silvicultural systems. This will mean fewer single species stands managed on patch clear felling regimes and more irregular stand structures containing a mixture of species and managed under Continuous Cover Forestry (CCF) regimes. However, the impacts of such changes on the forestry-wood chain are not clear, since MACDONALD *et al.* (2010) show that certain forms of CCF can result in a reduction in the timber quality of Sitka spruce. MASON (2007) estimated that changes in Scottish forests to accommodate multipurpose management might result in a 20 per cent or greater decline in conifer plantation area by 2030 with consequent declines in long-term timber supplies.

A further complication is that the future management of these plantation forests needs not only to respect the demands imposed by meeting the objectives of multi-purpose forest management, but must also consider how best to increase their resilience to projected climate change. Modelling of changes in the French climate suggest that a Mediterranean climate, defined by a water balance of less than 350 mm $year^{-1}$, would cover between 60 and 80 per cent of mainland France by the end of the century with consequent changes in the distribution of the main timber producing species (CACOT and PEYRON, 2009). Similarly, RAY (2008) has used projections of climate change to predict that parts of eastern Scotland will become unsuitable for growing Sitka spruce by 2080, because of decreased soil moisture availability during the growing sea-

son. There is also the concern that climate change may increase the likelihood of damage by pests and pathogens or by extreme events, such as the wind damage caused by storm Klaus in south-western France in January 2009 when 37.1 Mm^3 of maritime pine were blown down or broken, equivalent to five years annual harvest in the region (IFN, 2009b).

In the plantation forests of the Atlantic region, a range of silvicultural systems can be used ranging from intensive clear felling with artificial regeneration to the fostering of irregular stand structures based on natural regeneration (MALCOLM *et al.*, 2001). This variety of silvicultural systems coupled with the different tree species, site and climatic conditions can make it difficult to compare forest management approaches and their potential impacts on indicators of sustainability at either a country or a regional scale. In this paper we use a framework for classifying forest management options at a European level (DUNCKER *et al.*, 2008) to show how these options provide varying combinations of timber and non-timber outputs, and consider the interaction with silvicultural strategies proposed to adapt forests to climate change. This analysis is mainly based upon our experience with the Sitka spruce forests of Scotland and the maritime pine forests of south-western France.

A FRAMEWORK FOR CLASSIFYING FOREST MANAGEMENT OPTIONS

DUNCKER *et al.* (2008) have outlined the concept of Forest Management Alternatives (FMAs) whereby each FMA consists of a particular pattern of stand development supported by characteristic forest operational processes. These are operations such as soil cultivation, weed control, thinning and timing and extent of felling. FMAs can be defined by the general management objectives and a corresponding intensity of forest resource manipulation. They identified five FMAs in Europe which, arranged in order of increasing intensity of wood biomass removal, are:

- Unmanaged forest nature reserve (FMA 1);
- Close-to-nature forestry (FMA 2);
- Combined objective forestry (FMA 3);
- Intensive even-aged forestry (FMA 4);
- Wood biomass production (FMA 5).

Features used to distinguish between these FMAs include: species composition, management of stand density and/or pattern, age pattern/ phases of development, stand edges/ boundaries, amount and intensity of timber and biomass removal, and site conditions. The amount of external energy used in operational processes also differs between management alternatives.

The salient characteristics of each FMA are outlined below.

Unmanaged forest nature reserve (FMA 1)

The main objective of an unmanaged forest nature reserve is to allow natural processes and disturbances (e.g. windthrow) to create natural, ecologically valuable habitats. It will tend to be dominated by stands in the old growth and understorey reinitiation phases (*sensu* OLIVER and LARSON, 1996). No operations are allowed in a forest reserve that might change the nature of the area. Examples of this FMA in the plantation forests of the Atlantic region are rare, although some stands in Britain managed as biological retentions are developing this type of structure (PETERKEN *et al.*, 1992; HUMPHREY, 2005).

Close-to-nature forestry (FMA 2)

The aim here is to manage a stand with the emulation of natural processes as a guiding principle. Financial return is important, but management interventions must enhance or conserve the ecological functions of the forest. Timber can be harvested and extracted, but some standing and fallen dead wood is left, which may reduce productivity. Only native or site adapted tree species are chosen. Natural regeneration is the preferred method of establishing new seedlings. The rotation length is generally much longer than the age of maximum mean annual volume increment (MMAI) and harvesting uses small scale removals resulting in the development of an irregular and intimately mixed stand structure. The silvicultural systems characteristic of this FMA would be single tree and group selection, plus irregular shelterwood (terminology follows MATTHEWS, 1989). This type of management is being introduced into Sitka spruce forests in Scotland (MASON, 2003) and Ireland (NI DHUBHAIN, 2003), and similar structures can be found in old maritime pine stands in Les Landes managed to stabilize coastal dunes (SARDIN, 2009).

Combined objective forestry (FMA 3)

In this FMA, management pursues a combination of economic (timber production) and non-market objectives. Mixtures of tree species are often promoted, comprising both native and introduced species suitable for the site. Natural regeneration is the preferred method of restocking, but planting is also widely used. Site cultivation and/or fertilisation may be carried out to speed up the development of a young stand. The rotation length is similar to the age of MMAI and the harvesting system is generally designed around small scale clear felling with groups of trees retained for longer periods to meet landscape and biodiversity objectives. A number of shelterwood silvicultural systems (uniform, group, strip) are practiced in this FMA, as well as small patch clear felling. Forest management aims to produce sawlogs as a primary timber product. This type of management is found throughout the region wherever landscape or other non-market aspects are important objectives of management.

Intensive even-aged forestry (FMA 4)

The main objective in intensive even-aged forestry is to produce timber, although landscape and biodiversity may feature as secondary objectives. Typical stands tend to be

even-aged, and are composed of one or very few species. Any species can be suitable provided it is site adapted and non-invasive, and planting is the preferred method of regeneration. Intensive site management including cultivation and weed control is used to ensure rapid establishment. Genetically improved material is often planted when available. The rotation length is often less than or similar to the age of MMAI and clear felling is normal practice, although seed tree systems may be used on less fertile sites where wind hazard is low. Stands in areas of high wind risk may not be thinned. In some cases, whole tree harvesting may occur but logging residues (including branches and root systems) are normally left on site. This is the typical management approach in much of the region (e.g. Rodriguez-Soaillero *et al.*, 2000; ONF, 2003; Mason, 2007; CRPF Aquitaine, 2009) and Table 1 shows the main features of this FMA in Sitka spruce and maritime pine forests.

Wood biomass production (aka short rotation forestry) (FMA 5)

The main objective is to produce the highest amount of small dimension wood biomass or fibre. Tree species selection depends mainly on the economic return, as long as the species is not invasive. Pure stands of single species are generally favoured and intensive site management may occur to ensure rapid canopy closure. Stands cycle between stand initiation and stem exclusion with a short, rotation period i.e. from 5-25 years depending on species characteristics and the economic return. The intensity of harvesting is at its maximum compared to the other alternatives. The final felling is a clear-cut with removal of all woody residues, if there is a suitable market. Currently the eucalyptus plantations in Portugal and north-west Spain (Duncker *et al.*, 2008) would be the main example of this approach within the Atlantic region.

LINKING FMAS TO SUSTAINABILITY INDICATORS

Consideration of the various FMAs listed above and the different operations associated with each, indicates that they will have varying impacts on different aspects of sustainability. For instance, regimes favouring FMA 5 will tend to result in much lower levels of standing and fallen deadwood than is found under FMA 1, with a consequent reduction in biodiversity associated with the deadwood habitat (Brin *et al.*, 2008). Similarly, public preference for larger trees and more diverse structures is likely to result in higher valuation being given to forests managed under FMAs 1 or 2 than under FMAs 4 and 5 (Edwards *et al.*, 2011). By contrast, supplies of timber of regular dimensions and quality are likely to be greater under FMA 4 than under FMA 2, particularly when the benefits of

Table 1 A list of the main features characteristic of current plantation management (equivalent to FMA 4) for Sitka spruce forests in Scotland and maritime pine forests in Les Landes, France (see note for data sources)

Feature	Sitka spruce	Maritime pine
Genetic improvement	First generation seed orchard to cuttings of full sib families (10–30% genetic gain)	First and second generation seed orchards (15%–30% genetic gain respectively)
Ground preparation	Mounding (scarification on some drier soils)	Ploughing (complete or partial)
Drainage	Yes	Yes
Planting density (trees ha^{-1})	2,700	1,000–1,400
Weeding	1–3 times: chemical or hand	2–3 times: mechanical
Chemical protection	Against large pine weevil (*Hylobius abietis*)	In nursery, against large pine weevil (*Hylobius abietis*)
Fertilizer inputs	Rare	Recommended P_2O_5 60–80 kg ha^{-1}
Pruning	No	Rare 600 trees to 3 m at 6 m height; 400 trees to 6 m at 10 m height
Thinning	Only on 50 % of sites of lower wind risk; 2–3 times from years 20–25. Higher wind risk sites are unthinned.	3 to 5 times from years 15–30
Final stand density (trees ha^{-1})	300–1,000 (thinned – unthinned)	200–300
Rotation age (years)	35–50	35–60
Average productivity (m^3 ha^{-1} $year^{-1}$)	14	10.5

Note: the main data source used to compile this table was Duncker *et al.*, 2008, with additional information from Mason (2007) and ONF (2003).

genetic improvement are considered (MACDONALD *et al.*, 2010).

By formulating the relationship between a given FMA and indicators of sustainability, such as those proposed by the MCPFE (MCPFE, 2002), one can explore the impacts of changes in the balance of FMAs in a given country or region upon the future sustainability of the forestry wood chain (PAIVINEN and LINDNER, 2008). Such changes could arise as a result of new forestry policies, as described above for Scotland and Wales, or from the abandonment of agricultural lands as found in many mountain areas of Europe, or as a consequence of climate change. Ideally, the relationship between a FMA and a particular indicator should be quantified, as can be achieved for wood production using country specific or European growth models (NABUURS *et al.*, 2007a), but where quantitative data are lacking, qualitative measures involving expert judgment can be a helpful surrogate (EDWARDS *et al.*, 2011).

Within the EU 'Eforwood' project, a primary goal is to develop a computer-based tool for sustainability impact assessment ('ToSIA') for the European forestry wood chain (PAIVINEN and LINDNER, 2008; LINDNER *et al.*, 2010). A set of 27 indicators has been proposed to encompass the three pillars of sustainability: nine indicators under the 'economic' pillar, seven under 'social', and ten under 'environmental' (RAMESTEINER *et al.*, 2006). In the following section, we show how values of a subset of the Eforwood indicators can vary with FMA, using Sitka spruce forests in Scotland as an example.

FMAS AND SELECTED SUSTAINABILITY INDICATORS IN SITKA SPRUCE FORESTS

The estimates in Table 2 are based around a hypothetical stand of average productivity growing at 14 m^3 ha^{-1} yr^{-1}. It is assumed both that the risk of windthrow imposes no major constraint to management i.e. all FMAs are equally plausible on the site, and that there is no difference in productivity between FMAs in line with similar simulations of management options in British forests (MACDONALD *et al.*, 2010). The Net Present Value (NPV) calculations use 1 and 3 per cent interest rates and are based on the yields predicted by existing British yield tables (EDWARDS and CHRISTIE, 1981) for a stand of average productivity given normal thinning regimes. Management and other costs and revenues are derived from figures provided by MASON (2007). The yield models assume FMA 4 management and were extrapolated to other FMAs using expert judgement e.g. assuming proportionately lower yields for stands of Sitka spruce growing in mixture with other species. Timber quality and properties were predicted using models of wood density and tree taper developed by GARDINER *et al.* (2005). Recreational values were based on a 1–10 scoring system (a low score indicates a low recreational value and vice versa) (EDWARDS *et al.*, 2011). Biodiversity value was based on the same approach (M. Smith., Forest Research, pers.comm.) and inte-

Table 2 Estimates of values of a range of sustainability indicators by Forest Management Alternative (FMA) for an average productivity (14 m^3 ha^{-1} $year^{-1}$) stand of Sitka spruce in Scotland

Sustainability indicator	FMA				
	1: Unmanaged forest nature reserve	2: Close to nature forestry	3: Combined objective forestry	4: Intensive even-aged forestry	5: Wood biomass production
Assumed rotation length (years)	200	100	60	50	25
NPV @ 1% (euros/ha)	−5,200	4,620	3,260	4,850	2,370
NPV @ 3% (euros/ha)	−2,690	−750	−2,200	−1,400	−1,280
Recreational value (score 1–10)	5.9	6.7	4.4	3.6	2.8
Biodiversity value (score 1–10)	6.6	5.0	3.7	2.1	1.2
Carbon stocks (t C ha^{-1})	215	135	120	110	60
Machinery emissions (t CO_2 eq ha^{-1} yr^{-1})	0.01	0.06	0.09	0.10	0.16
Employment (FTE 100ha^{-1})	0.21	0.48	0.51	0.56	0.59

All values are for a base year of 2005.

grates a number of factors known to influence biodiversity and to be influenced by forest management (HUMPHREY *et al.*, 2003; RAULUND-RASMUSSEN *et al.*, 2008). These are: *structural features* such as vertical and horizontal structure within a stand, associated habitats such as open ground, and the presence and amount of dead wood; *compositional aspects* include ground flora, faunal diversity, tree and shrub diversity, and the abundance of epiphytes and fungi; lastly *functional attributes* comprise the naturalness of the stand and the continuity of woodland cover on the site. Calculations of carbon stocks, machinery emissions, and current and projected per cent forest area are based on MASON *et al.* (2009a). Lastly, the employment statistics are based on data from the late 1990s (FORESTRY COMMISSION, 2001) and include haulage of timber from forest to the mill as well as within forest operations. The statistics distinguish between establishment and harvesting operations and the figures were allocated by FMA assuming proportionately greater activity in both areas in FMA 4 and 5. The framework can be expanded to provide for other indicators of sustainability (e.g. soil nutrient status, water quality – RAULUND-RASMUSSEN *et al.*, 2008) as existing knowledge on the impacts of management on a particular indicator is collated.

FMA 4 is the traditional form of management for Sitka spruce forests in Scotland and produces a positive return at a 1 per cent interest rate and a negative one at 3 per cent. It provides a comparatively high rate of employment and maintains reasonable carbon stocks, but has comparatively low recreational and biodiversity value compared to some of the less intensive management alternatives. By contrast, close-to-nature forest management provides higher recreational and biodiversity values, maintains slightly higher carbon stocks, is slightly less profitable at a 1 per cent interest rate but produces a less negative result at a 3 per cent rate than FMA 4. This latter result is critically dependent upon the assumption that restocking in FMA 2 is achieved entirely by natural regeneration, thus reducing the establishment costs incurred in FMA 4 by operations such as site preparation and planting (see Table 1). However, if a 20 per cent genetic gain is built into the NPV calculations for FMA 4, the net effect is to almost eliminate the deficit for this option because of assumed improvements in sawlog yields (data not shown).

An interesting feature of these results is that combined objective forestry seems less attractive in either economic or socio-environmental terms than close-to-nature or intensive even-aged management. This is largely because the introduction of other species into a Sitka spruce matrix results in lower yields than in the pure Sitka spruce stands characteristic of FMA 4, while still incurring many of the establishment and management costs associated with the latter. Furthermore, the shorter rotation length compared to FMA 2 means that fewer biodiversity and recreational benefits are achieved, since these tend to be associated with older ages of stands (EDWARDS *et al.*, 2011). As would be expected, FMA 1 has the highest biodiversity value and a high recreational score, but the need to provide a basic level of management input (e.g. path and track maintenance, control of browsing animals) results in a negative financial outturn. The estimates for FMA 5 are affected by the lack of an established woodfuel market within the UK keeping prices for woodfuel products relatively low, while the intensity of harvesting and the rotation length result in lower recreational and biodiversity values.

An attraction of this framework is that one can link the indicator values with the proportions of different FMAs to explore the impact of different policy scenarios. In Table 3 we established the current and likely distribution of FMAs in Sitka spruce forests under a 'business as usual' scenario (year 2005 as a reference; EDWARDS *et al.*, 2011) and two other potential distributions of FMAs to compare their relative effects. In Table 4 we illustrate the consequences for some of the sustainability indicators discussed above. The two projected scenarios considered were: Natura 2000 and projected UK policy. The estimates of per cent forest area by FMA for 'Natura 2000' are based on those for all conifer forests in the UK (EDWARDS *et al.*, 2011) while that for 'projected UK policy' is taken from MASON *et al.* (2009a). The 'Natura 2000' scenario assumes greater emphasis is given to nature conservation in forests (EUROPEAN COMMISSION, 2003) and assumes that at least 15 per cent of the forest area is transferred to either FMA 1 or

Table 3 Percentage distribution of Forest Management Alternatives (FMA) for Sitka spruce forests in Scotland under 3 different scenarios (see text for details)

Scenario	FMA				
	1: Unmanaged forest nature reserve	2: Close to nature forestry	3: Combined objective forestry	4: Intensive even-aged forestry	5: Wood biomass production
Business as usual (reference)	0.5	7.0	22.0	70.0	0.5
Natura 2000	1.7	23.3	18.1	56.6	0.3
Projected UK policy	5.0	15.0	50.0	25.0	5.0

Table 4 Impact of 2 different scenarios upon relative values of selected sustainability indicators

Indicator	Scenario	
	Natura 2000	Projected UK policy
NPV @ 1%	0.98	0.77
Recreational value	1.13	1.13
Biodiversity value	1.17	1.32
Carbon stocks	1.04	1.06
Machinery emissions	0.92	0.92
Employment	0.97	0.94

Relative values are expressed as a ratio of those for the business as usual scenario (see text for details).

FMA 2 with restrictions on harvesting in these alternatives.

Both alternative scenarios show a switch away from FMA 4 towards less intensive management regimes in FMAs 1–3, but the change is less in the Natura 2000 scenario than under projected UK policy. The latter results in a greater proportion of combined objective forestry (FMA 3) and of unmanaged forest nature reserves (FMA 1) than the other scenarios. As a consequence, there are greater impacts on some important indicators such as a 23 per cent fall in NPV and 32 per cent increase for biodiversity compared with business as usual. By contrast the Natura 2000 scenario has minor effects on NPV (2 per cent reduction) while providing reasonable increases in recreation and biodiversity value (13 and 17 per cent respectively).

These findings are illustrative and make no allowance for possible changes within a FMA such as improved management leading to a higher sawlog outturn or the impact of changing market conditions like a strengthening in the demand for wood fuel. They also do not allow for any impact of the transition process necessary to move from one scenario to another. However, this framework provides a useful means of demonstrating the potential impacts of changes in forest management, such as the increasing concern to implement effective strategies to adapt Atlantic forests to projected climate change.

SILVICULTURAL STRATEGIES FOR ADAPTING FORESTS TO CLIMATE CHANGE

Examination of recent British and French guidance on adaptation of forests shows broad agreement on the general measures to be implemented over the next decade (e.g. Cacot and Peyron, 2009; Mason *et al.*, 2009b). These measures can be interpreted as a recommendation for greater diversification of forests as part of risk planning, including use of provenance mixtures, fostering mixed species stands, lengthening rotations, more thinning especially in areas at risk from drought, development of more stable stand structures, and the use of a wider range of silvicultural systems. An additional point identified by Cacot and Peyron (2009) is the desirability of testing new genetically improved varieties of maritime pine for their potential sensitivity to drought. Taken as a whole, these recommendations could be seen as an endorsement of policies that seek to increase the representation of FMAs 1–3 in Atlantic forests at the expense of FMA 4.

However, these adaptation principles are, as yet, too general to be of practical use in forest management. The advice to diversify forests, for instance by transforming more forests to FMA 2 from FMA 4, overlooks the fact that the thinning operations necessary to implement this transformation can increase the vulnerability of the thinned stands to windthrow, especially in the oceanic climate of Atlantic Europe (Mason, 2003). The converse is that intensive thinning of young stands managed under FMA 4, as practiced with maritime pine, can increase the risks of windthrow since there is insufficient crown contact to provide within stand stability and individual trees become vulnerable to strong winds (Cucchi and Bert, 2003). These increases in risk as a consequence of thinning are without considering any possible effect of climate change on the occurrence of extreme events, such as storms or summer droughts. Furthermore, the prescription to lengthen rotations overlooks the fact that younger stands which are actively managed have greater flexibility to withstand climate change, whereas older stands show less resilience and can be vulnerable to extreme events (Nabuurs *et al.*, 2007b).

In addition, one impact of the warming climate, when coupled with higher CO_2 concentrations and greater nitrogen deposition, could be to increase forest growth rates in the Atlantic region (Pussinen *et al.*, 2009). These authors project that, for this zone[1], net primary production will increase by 115–153 per cent by the end of the century from the current level of 7 t C ha^{-1} yr^{-1} while similar increases are projected for tree and carbon stocks. They identify higher felling levels as one option open to foresters to allow increase the forests' resilience to climate change. Thus, adaptation of Atlantic forests to climate change may also need to consider more sophisticated management of FMA 4 stands including deployment of improved genetic material which may also provide higher quality timber to substitute for more carbon intensive materials (e.g. steel, concrete) used in construction.

DISCUSSION

In other parts of the world, it is possible to consider meeting the demands of multi-purpose forest management by

[1] Note that for Pussinen *et al.* (2009), the Atlantic region excludes Portugal and parts of Spain and includes more eastern parts of the UK and France, and all of Denmark, Belgium, Netherlands, Luxemburg.

focussing wood production in relatively small areas of intensively managed plantations while the range of ecosystem services are provided by extensively managed natural forests. However, in the Atlantic region, the history of deforestation followed by reforestation with plantations means that it is the plantation resource which has to be managed in a variety of ways to ensure the supply of a full range of ecosystem services. In the British Isles this can be seen in recent forestry policy statements, where, for example, the recent Welsh forestry strategy seeks to progressively reduce reliance upon clearfelling (i.e. FMA 4) in favour of a range of alternative silvicultural systems (i.e. FMAs 2 and 3) (ANON., 2009a, p 19). Such changes can have substantial impacts upon other aspects of the forestry wood chain, such as the available supply of timber over time and the employment provided, or the rates of carbon sequestration achieved within forest stands. However, it can be difficult for policy makers and forest managers to explore the potential impacts of such policy changes without access to a framework that links possible management alternatives to a range of important sustainability indicators. The attraction of the FMA structure presented in this paper is that it provides a simple framework which is capable of being applied across a range of forest types (DUNCKER *et al.*, 2008) and provides a transparent means of exploring trade-offs between different silvicultural approaches (e.g. PIZZIRANI *et al.*, 2010). The importance attributed to different indicators can be adjusted through relative weightings derived in discussion with stakeholders, for instance through techniques of multi-criteria analysis (WOLFSLEHNER *et al.*, 2005). When coupled with growth models, the approach can be used to examine changes in sustainability over time, as has been shown through the use of the growth simulator EFISCEN (SCHELHAAS *et al.*, 2007) to help estimate recreational benefits (EDWARDS *et al.*, 2011), and it could also be combined with GIS to provide geospatial information (ALVAREZ and FIELD, 2009).

The results presented in Tables 2 and 4 are based on the assumption that all FMAs are equally plausible, but in reality there are different abiotic and biotic risks associated with these options. In the Atlantic region there is a history of severe damage from wind (e.g. in Scotland in 1953, 1968, 1976 and 1998; in Les Landes in 1976, 1996, 1999 and 2009; BESSEMOULIN, 2009) and the non-thin and shorter rotation policy adopted in Sitka spruce stands on more exposed sites in Scotland (MASON, 2007) can be seen as a means of adapting management to climatic risk. On such sites it is unrealistic to assume that transformation to FMA 2 is a possibility and therefore the choices are restricted to FMA 3–5. The hazards associated with climate change are not merely dependant upon a FMA but are also influenced by species and site characteristics. For instance, in northern Britain the vulnerability of lodgepole pine (*Pinus contorta* DOUGL.) stands managed under a non-thin variant of FMA 4 is often much greater than for Sitka spruce on the same site type, because of the greater susceptibility of the former to the needle cast fungus *Dothistroma septosporum* (BROWN and WEBBER, 2008).

Successful delivery of policies to increase resilience of Atlantic plantation forests will ultimately depend upon identifying those sites and stands at greatest risk from climatic impacts and using site based silviculture to undertake appropriate remedial actions. This will require an integration of probabilistic modelling of the occurrence of an extreme event, such as provided by the ForestGALES wind risk model (GARDINER *et al.*, 2006), with predictions of species response to soil moisture availability, as through the Ecological Site Classification (RAY *et al.*, 2002). These predictions can be linked to site and stand characteristics and projections of anticipated climate change to identify those areas of forests most at risk. A possible structure of a vulnerability classification would be to identify those stands that would be vulnerable within the next 10 years, those that could be vulnerable within 20–25 years, and those that might be vulnerable in a longer timeframe. The first category could become a priority for actions such as a change of species or provenance; the second might be where remedial silvicultural measures such as more intensive thinning were undertaken, whilst the third would remain under the current silvicultural regime, but with regular monitoring to check that no unforeseen hazards were developing. Such a framework could also be used to incorporate improved knowledge of the potential impact of a range of pests and pathogens, especially how these might be affected by silvicultural regimes (JACTEL *et al.*, 2009).

CONCLUSIONS

Adapting Atlantic forests to climate change presents a number of research challenges. The eight priorities listed below were developed for forests in the UK (MASON *et al.*, 2009a), but we believe that these may be generally applicable throughout the Atlantic region:

1. Develop methodologies to help forest managers identify sites and stands most vulnerable to climate change;
2. Development of data-bases/knowledge on how different species/provenances are expected to respond to climate change (e.g. climate envelope modelling) matched by studies on how their populations and distributions are actually changing;
3. Improved understanding of the factors that will become limiting for species at a regional level;
4. Trialling of species/provenances/genetically improved varieties that may be suitable for the current and projected Atlantic climate;
5. Improved understanding of how climate change will alter disturbance regimes of wind, fire, pests and diseases;
6. Improve predictions of changes in wind climate and adapt existing wind risk models to predict vulnerability of more varied stand structures;
7. Adaptation of growth models developed for even-aged forests of single species to more diverse forest types and/or provision of more flexible models;

8. Improved understanding of appropriate decision-making methods-including methods of dealing with uncertainty and the integration of multiple societal values as illustrated here using the FMA approach.

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Review

Depletion of Tropical Forest Resources, Prevention Strategies, Remaining Challenges and Implications for Action

Mangala De Zoysa* and Nesha Dushani*

ABSTRACT

The area covered by tropical forests is rapidly shrinking, and local wood shortages, land degradation, biodiversity loss and global warming are been recognized as the main negative impacts. This paper review literature and examines the depletion of tropical forests and implemented prevention strategies and discusses the remaining challenges to protect and implications for actions to restore the forests. The tropical forests are disappearing by 0.18% per year at a rate of 32,000 ha per day falling global per capita forest area to 0.6 ha in 1990 and projecting less than 0.2 ha by 2020. The tropical forests have been over-exploited creating serious threat on the production of forest goods and services. Some of the major global strategies proposed and implemented during the last few decades to combat tropical forest depletion include Tropical Rainforest Campaign in 1975; straightforward protected areas approach in 1980s; community forestry approaches in 1980s; market-based forest management after 1986; Tropical Forests Action Plan in 1987; The forest policy of World Bank in 1991; the integrated conservation and development programs through "Earth Summit" in 1992; forest certification in 1993; Millennium Development Goals in 2000 and Kyoto Protocol. Major challenges remaining in protection of tropical forests are recognized as the shifting socio-economic conditions of the countries; globalized financial markets; the worldwide commodity boom; and wood based industrial promotions. Many community-based forestry management strategies have currently become inappropriate without considerable external support. Eco-certification has hampered by corruption and weak governance while Kyoto Protocol has been defeated for political reasons. The international agreements and conservation programs have to be coordinated by the establishment of appropriate mechanism for coordination, consultation, and collaboration to conserve tropical forests. Dialogues and education campaigns among scientific, industrial and conservation interests have become a vital importance to slow harmful forest depletion with industrialization trends. Food security oriented forestry strategies and multipurpose forestry programs could be able to supply forest services and products to meet changing social, economic and environmental circumstances. Community forest governance would promote the sustainability of forest management with growing array of stakeholders, changing to multi-centric structures, and differences in scales, goals and means of forest management.

Keywords: depletion of forests, prevention strategies, challenges for protection, actions to restore forests

INTRODUCTION

Tropical forest is a type of forest grows in winterless tropical climates with high temperatures and generally high annual rainfall and consisting of heavy canopy broad-leaved tree species. Tropical forests provide vital ecological functions such as maintaining biological diversity; modulating precipitation, infiltration of water; protecting and enriching soils; regulating the hydrologic cycle; and helping stabilize the global climate (Wikipedia encyclopedia). Tropical forests and savannahs store around 340 billion metric tons of carbon play a crucial role in the global cycling of carbon (Ehrenberg, 2009). Tropical forests reduce erosion and act as buffers against flooding regionally. Tropical forests perform a wide range of social services including providing livelihood for forest dwell-

Corresponding author: Mangala De Zoysa
E-mail: mangala@agecon.ruh.ac.lk
* Department of Agricultural Economics, Faculty of Agriculture, University of Ruhuna, Mapalana, Kamburupitiya, Sri Lanka

ers, increasing scientific knowledge, and improving the spiritual well-being of humans. More than 1000 indigenous tribes still survive in tropical forests. Tropical forests play an important role in contributing to the food security in most of the developing countries (GBETNKOM, 2008). It has been revealed that over one-quarter of modern medicines have originated from plants (TAYLOR, 2004). A number of products and by-products including timber, charcoal, firewood, pulp, tannin, lignin, cellulose and wax are directly obtained from trees. Over two billion people, particularly in households in developing countries use wood as the dominant source of energy (FAO, 2008).

Depletion of tropical forest resources has become a severe global phenomenon. During the late 1980's attention to the rapid rate of tropical deforestation was accelerated with the emerged of concern about global climate change. The productive closed forests managed for wood production was 42 M ha or 4.7% of the total area in the tropic in 1980 (LANLY, 1982). The area covered by tropical forests around the world is rapidly shrinking as a result of severe logging and agricultural clearance. Farmers, ranchers, logging and mining companies, and fuelwood collectors often cause deforestation. Local wood shortages, land degradation, global warming, and biodiversity loss have been recognized as the main negative impacts of the forest depletion. However, depletion of global forest trends is expected to continue unless proper and effective measures are activated. The time has come to work hard internationally, regionally and locally, and to protect, manage and restore the forests by identifying challenges and developing actions. Hence, this paper attempts to review the literature and ascertain the depletion of tropical forest resources, analyze the past strategies implemented to prevent forest depletion, examine the remaining challenges to combat forest depletion, and discuss possible implications for action.

DEPLETION OF TROPICAL FORESTS AND FOREST RESOURCES

Extent of the Forest Depletion

The forest area has decreased worldwide by 0.22% per year during the period of 1990-2000 and 0.18% per year between 2000 and 2005. The tropical regions in the world have already lost over two-thirds of their original cover (WILCOX, 2005). According to a FAO study, the world lost 450 M ha of its tropical forest cover between 1960 and 1990. Tropical rainforests are disappearing at a rate exceeding 32,000 ha per day. It has been reported that at least 250 M ha of forests vanished between 1980 and 1995 alone (ABRAMOVITZ, 1998). The Natural Resources Defense Council (NRDC) assumed that the global wood consumption will double over the next 30 years. It has been estimated that the global per capita forest area had fallen from an average of nearly 1.2 ha in the 1960 to 0.6 ha in 1990 and it is projected to be less than 0.2 ha by 2020 (FAO, 1995). The extent of world's forests decreased by about 180 M ha between 1980 and 1995 as the result of a net loss of 200 M ha in developing countries and a net increase of 20 M ha in developed countries (MARCOUX, 2000). According to the UN-DESA (2009), deforestation still continues at the rate of about 13 M ha per year. Even with partially counterbalanced of forest by forest planting, landscape restoration and the natural expansion of forests, net global loss over the period 2000-05 is estimated at 7.3 M ha per year, down from 8.9 M ha per year during 1990-2000.

Causes of the Forest Depletion

The impact of human activities on tropical forest depletion dependent on the extent of intensification of agricultural production and economic activities including clearing, grazing, burning, forest exploitation, hunting, gathering and mining. Detailed satellite images of changes in land use in the tropics shows that 80% of new cropland came from clearing forests during the period from 1982 to 2000 (EHRENBERG, 2009). More than half of cropland expansion has occurred in natural forest while another 30% occurred in disturbed forests during the period from 1980 to 2000 (BUTLER, 2005). Export crop prices, food crop prices and timber export price are vital in stimulating the clearing of forests (GBETNKOM, 2008). It has been estimated that more than 38,600 square miles of tropical forest has been cleared for pasture by cattle ranches since 1996 (BUTLER, 2005). Almost half of the trees cut in the world mostly in developing countries are used for fuel and charcoal (FAO, 2008). Most of the trees cut in arid and semi-arid countries are to meet the fuel requirement. Government policies for rural development in many developing nations largely promoted tropical forest destruction from the 1960s to 1980s (BUTLER and LAURANCE, 2009). Illegal logging alone accounts for losses of US$10 to $15 billion per year from public forest lands (WORLD BANK, 2004). It is estimated that the illegal logging equal or exceeding the legal harvest rates in Cameroon (50%), the Brazilian Amazon (90%), Bolivia (90%), Indonesia (51%), Myanmar (80%) and Cambodia (94%). Not only limited to developing countries, illegal logging also is a persistent problem in USA, Canada and Russia. Illegal logging activities primarily associated with commercial scale even in protected areas and outside of concession boundaries.

Impacts of Forest Depletion

Depletion of forest cover in tropical zones is having serious effects on the production of forest goods and services. Logging and conversion of forestland into agricultural use to short-term are results in destruction of the land, erosion and flooding. Species extinction, the loss of important ecosystem services and renewable resources, and the reduction of carbon sinks are some of the major impacts of forest depletion. Species in tropical rainforests possess a high degree of mutuality for their survival becomes endangered when the trees are cut down (US OFFICE of TECHNOLOGY ASSESSMENT, 1992). The

large-scale plantation project in tropics have neglected need to diversify species and to conserve some natural forests in the long run proved disastrous. It has been estimated that world is losing more than 137 species of plants and animals every single day because of deforestation. Nearly half of the world's estimated 10 M species of plants, animals and microorganisms will be destroyed or severely threatened over the next quarter-century (TAYLOR, 2004). The tropical forests in the world hold 460-575 billion Mt of carbon per year. Deforestation of tropical forest is a massive source of carbon emissions and contributes significantly to global warming and atmospheric change (LAURANCE, 2007). High levels of deforestation and forest degradation particularly in developing countries accounted for 17.4% of total anthropogenic greenhouse gas emissions in 2004 (UN-DESA, 2009)

PAST STRATEGIES IMPLEMENTED TO PREVENT FOREST DEPLETION

Forests Conservation Strategies

Conservation organizations emphasized a simpler and more straightforward protected areas approach keeping people out with fences and guards as much as possible (KAIMOWITZ, 2003). The first Tropical Rainforest Campaign of WWF in 1975 raised money and arranged for representative tropical rainforest areas in Central and West Africa, Southeast Asia, and Latin America, to be managed as national parks or reserves. The world's total forest protected areas reached 480 M ha, or roughly 12% of all the planet's forests by 2000. Following the recommendation of the Stockholm Conference held in 1978, FAO and UNEP undertook a joint program of forest resources assessment within the framework of the Global Environment Monitoring System (GEMS). The program was an initiative that governments and the international community could be made aware of the trends affecting the world's forests (LANLY and CLÉMENT, 1979). UNCED – Rio (Earth Summit) in 1992 brought together 172 governments was an important event in the international debate on forests. The Summit adopted a statement of "Forest Principles" and devoted a chapter of Agenda 21 to measures to combat deforestation and formed the Commission on Sustainable Development (CSD), the Convention on Biological Diversity (CBD), the UN Framework Convention on Climate Change (UNFCCC – precursor of the Kyoto Protocol), and the Intergovernmental Panel on Forests (IPF) later in 1995.

Community Forestry Projects

Forest conservation and sustainable rural development approaches in 1980s were based on the notion that small-scale farmers and shifting cultivators were responsible for most of the tropical forest depletion (BUTLER and LAURANCE, 2009). The international recognition of community forestry was emerged in 1980s as a strategy to address widespread forest loss, and its adverse environmental consequences and negative impact on rural livelihoods assuming that the best stewards of forests are the local community (GILMOUR *et al.*, 2004). The community forestry is an institutional arrangement in which communities share in decision-making and benefits, while contributing labor and experience to achieve healthy forests and social well-being. It was believed that indigenous peoples or local communities would manage forests if there are granted rights over forests, help resolve competing claims by similar groups, and take steps to restrict encroachment by outside farmers, ranchers, loggers and miners (KAIMOWITZ, 2003). It was expected that the communities manage, use and control the forest and tree resources respecting the social, economic and cultural relationships between people and forests (FAO, 1997). The community forestry promotes community and protects their rights through capacity strengthening, economic empowerment, sustainable resource management and technical support. Community based forest management involves in wide rage of situations including conservation of forest environment, development of woodlots in areas which are short of wood and other forest products for local needs, growing of trees at the farm level to provide cash crops, and the processing of forest products at the household to generate income (FAO, 1978).

Integrated Forest Conservation and Development Programs (ICDPs)

The forest policy of World Bank in 1991 declared an end to tropical deforestation as its central goal. The "Earth Summit" in Rio de Janeiro in 1992 (UNCED) implied the "Integrated Conservation and Development Programs" (ICDPs) to achieve "win-win" solutions. Reforming forest concession policies, introducing voluntary certification, and training people in reduced impact logging were the major efforts of ICDPs to make large-scale tropical timber production sustainable (KAIMOWITZ, 2003). The World Bank Forest Investment Fund has proposed to establish $300 - 500 million for financing governments efforts to reform the forestry sector and private sector to protect remaining major stands of forest and reduce deforestation. The International Tropical Timber Organization (ITTO) was established in 1986 to facilitate discussion, consultation and international cooperation on international trade and utilization of tropical timber, and the sustainable management of its resource base. All 53 ITTO member countries had pledged to manage their forests sustainably by the year 2000 under the 'Sustainability 2000' agreement (ITTO, 1996). The Tropical Forests Action Plan was launched in 1987 following international concern over the rate of deforestation in the tropics. The World Bank/WWF Alliance for Forest Conservation and Sustainable Use was formed as a strategic partnership in response to the continued depletion of the world's forest loss and the consequent impacts. The contribution of forest and trees in addressing poverty was given priority in the Millennium Development Goals in 2000. The major concerns were based on

the fact that 240 M poor and heavily forest-dependent people in developing countries, 2.4 billion people get their energy mostly from biomass fuels, and several billion people rely on medicinal plants as their primary source of health care. The strategy has great progress and they are now own or have long-term usufruct rights over about one-fifth of the forest in developing countries (KAIMOWITZ, 2003).

International Carbon Markets to Slow Deforestation

The Clean Development Mechanism (CDM) of the Kyoto Protocol proposed to use international carbon markets to slow deforestation (LAURANCE, 2007). The first point of accounting for national reductions and endorses international carbon trading has identified the period of 2008-12. The Protocol sets the target of reducing emissions by an average of 5.2% below 1990 greenhouse gas levels by the year 2012 (CARBON TRADE WATCH, 2009). The Coalition for Rainforest Nations an alliance of 15 developing countries led by Papua New Guinea and Costa Rica, again attempted to revive efforts to use carbon credits to slow deforestation (LAURANCE, 2007). Approximately 17% of global greenhouse gas emissions are associated with deforestation and forest degradation (HOUGHTON, 2005). World Bank is managing various investment funds for the implementation of international Reducing Emissions from Deforestation and Degradation (REDD) mechanism. The World Bank Bio Carbon Fund was established in 2004 to demonstrate projects that conserve carbon in forest and agro-ecosystems. The World Bank Forest Carbon Partnership Facility (FCPF) was launched in December 2007 with a target of $300 million, of which $165 million has been pledged. The FCPF funding likely to be spent over five years, beginning in 2008, for 20 countries to support the development of country Readiness Action Plans and Carbon Finance Mechanism. The growing market for ecosystem services will generate extra revenues and the funds may greatly help for forest conservation (BIOPACT, 2008).

Forest and Forest-products Certification

Certification programs have been established by the owners of forest resource, governments, and NGOs to certify timber products produced in an environmentally sustainable manner (FLETCHER, 1995). Forest certification is intended as an approval of notifying consumers that a wood or wood product comes from forests managed in accordance with strict environmental and social standards. Certifiers also grant "chain-of-custody" certifications to companies that manufacture and sell products made out of certified wood. A chain-of-custody assessment tracks wood from the forest through milling and manufacturing to the point of sale. Smart Wood, the world's first independent forestry certifier, introduced the concept of forest and forest-products certification. About 20 organizations were developing certification systems by 1995 (FLETCHER, 1995). The Forest Stewardship Council (FSC) and the Sustainability Forest Initiative (SFI) are the most widely used in determining whether wood is sustainable. The Forest Stewardship Council (FSC) was established in 1993 to provide standard setting, trademark assurance and accreditation services for companies and organizations interested in responsible forestry. The Forest Stewardship Council (FSC) is a voluntary effort involving NGO, industry and government participants. Currently there are over 104 M ha of FSC Certified Forests with nearly 6 million species. Green certification of the wood is a relatively new development within the industry and standards are still evolving.

REMAINING CHALLENGES IN COMBATING FOREST DEPLETION

Changing Socio-economic Conditions, Financial Crisis and Development Strategies

The global economy has tripled in size and the world population has increased by 30% since 1980 (TAYLOR, 2004). One of other hand major underlying causes of deforestation and species extinction in the tropical countries is the lack of alternative employment for the growing populations (US OFFICE OF TECHNOLOGY ASSESSMENT, 1992). Creation of economic incentives for conservation should be the central part of a conservation strategy in developing countries where enforcement is often difficult. Although conservation projects direct local farmers for different other jobs, local demand for food, fiber, forest products and energy does not disappear. Since many rural people could not survive without subsistence uses and cash income from forests, it is not certain how much the forests could assist in getting people out of poverty under the effort of Millennium Development Goals and addressing poverty (KAIMOWITZ, 2003). "Avoided Deforestation" (AD) policy which is referred to as Reduced Emissions from Deforestation (RED) under UNFCC pay relatively little attention to the potential impact on indigenous peoples and local communities (WRM, 2007). Most tropical developing countries could not set aside more than 10 or 15% of the tropical forests as protected areas because it is not possible to ignore a large number of people live inside the protected areas (KAIMOWITZ, 2003). The current global financial crisis has threatened the initiative to increase forest coverage in the developing countries as a means to combat climate change. It is believe that the conservation approach has largely failed because the local communities use the funds to promote their income rather than to replace the benefits they gain from exploiting forest resources (BUTLER and LAURANCE, 2009). International agencies and developing country governments are rarely focused on forest conservation but concentrated on addressing extreme poverty where more than one billion people earn less than US$1 per day. The loss of forest in 1990s continued at the rate of 12-15 M ha million per year as in 1980s (KAIMOWITZ, 2003). Governments' activities such as settlement of land through cheap credit, subsidized large-

scale agriculture development programs, and the building of roads and infrastructure often led to the destruction of forests.

Inappropriateness of Community Forestry

Efforts to put Community Forestry into practice have achieved only modest result due to the need of considerable external resources to overcome the technical, legal and financial barriers. Without considerable external support to overcome technical, legal and financial barriers it is impossible for communities to engage in legally recognized forest management activities (POKORNY and JOHNSON, 2008). Although the community forestry combine environmental, social and economic development in theory, it is impossible for governments to develop and apply appropriate regulations under wide variations in socio-economic and environmental contexts. Various training events and forest operations under community forestry mean additional work for the communities. All the members of the community are not able or interested in investing the required time resulting in tensions over how to distribute responsibilities, costs and income. Commercial enterprises are considered to be the only actors with the financial and technical capacity for appropriate forest management since the Rio summit in 1992 (POKORNY and JOHNSON, 2008).

Deforestation Accelerated by Globalized Financial Markets and Industrialization

The International Tropical Timber Agreement (ITTA) has negotiated the governing trade in tropical timber. However, it could address only the formal tropical timber trade which is estimated to cause only 5% of global deforestation (FLETCHER, 1995). The eight largest industrial countries in the world are accounting for 74% of the world's timber imports (LARSEN, 2002). Illegal logging has becomes a complex problem in timber producing countries with involvement of financiers of illegal logging, including national and international banks, legal timber industries and government officers (SETIONO and HUSEIN, 2005). Malaysia, Indonesia and Brazil, have pressures on their remaining forests due to the need to service and markets for wood products in industrialized countries (TAYLOR, 2004). Fifty-seven percent of the logs brought illegally into China originate in Russia (LARSEN, 2002). Deforestation was often a direct consequence of the export-oriented policies imposed by the World Bank/IMF Fund. Economies of the Third World have been systematically opened via Structural Adjustment Programs (SAPs) of the World Band/IMF for the direct benefit of the Third World elites and Northern lenders (BELLO, 1996). There are international incentives for granting logging rights to cut down the tropical rainforests to make plywood, ornamental moldings and furniture. Globalized financial markets and the worldwide commodity booms are aggravating industrial logging, mining, industrial farming and large-scale agriculture, and bio-fuel production, while increasingly emerging as the dominant drivers of forest depletion. The tropical forests once laboriously hand cleared by small-scale farmers, are now being quickly overrun by machines such as bulldozers. Tropical deforestation will be simply good business with the increase of global industrial activities which is expected to expand 300-600% by 2050 (BUTLER and LAURANCE, 2009). The green sheen of bio-fuel would disappear they are grown in tropical forests which could lead to severe deforestation and release more carbon into the atmosphere (FAO, 2008). Many countries including tropical countries are presently aiming to replace fossil fuels with bio-fuels even without agricultural land to grow these fuels. These countries will have to clear and burn tropical forest in order to grow most promising bio-fuel crops such as sugarcane and palm oil (EHRENBERG, 2009).

Resistance for Implementation of Kyoto Protocol

Within the first implementation period of the Kyoto Protocol (2008-12), avoiding deforestation was not included as an emissions reduction mechanism. REDD was agreed at the Framework Convention on Climate Change Conference of Parties (COP13) in Bali in 2007. Europe opposed the idea of the Kyoto Protocol that wealthy nations might "buy their way out" of part of their international obligations to control emissions, rather than making substantial and permanent emissions reductions. Developing countries opposed carbon trading because their national sovereignty issues are sensitive. They believe that accepting reduced-deforestation funds from industrial nations could potentially limit their future development options (LAURANCE, 2007). Needs of forests for fuel and livelihood in developing countries are claimed as too great to be set aside for the sake of the environment. Many developing countries including Costa Rica and Papua New Guinea argue that they will never receive adequate and sustained finance for avoided deforestation (WRM, 2007). The USA resisted signing international treaties and agreements on climate change. They argue that the major emerging economies should be accountable for heavy industrial pollution even though they are developing countries (MELÉNDEZ-ORTIZ, 2009).

Institutional Irregularities

Many corporations have been accused of producing green products that actually have little environmental benefits. Unilever Ltd used palm oil grown on recently deforested land has diminished its good-image which had been developed for making effort toward sustainability (BUTLER and LAURANCE, 2009). Industry-sponsored groups in the tropical timber industry try to compete with legitimate eco-certification bodies. National environmental groups allege that the Indonesian Ecolabel Institute is facilitating rainforest destruction by issuing "sustainable forest management certificates" to companies that convert natural forest into industrial timber estates (BUTLER, 2005). Even the FSC, has been heavily criticized by Wall Street

Journal for certification of the Singapore-based Asia Pulp and Paper Company because of its environmentally damaging activities on the Indonesian island of Sumatra (BUTLER and LAURANCE, 2009).

IMPLICATIONS FOR ACTION

Coordination of Global Forest Conservation and Environmental Concerns

Internationally coordinated programs to combat problems associated with tropical forest degradation have to be coordinated at sub-regional and regional levels by the establishment of appropriate mechanism for coordination, consultation and collaboration for the greater effectiveness. International agreements – such as the UN Framework Convention on Climate Change and the Convention on Biological Diversity – could mediate the industries promoting forest depletion (BUTLER and LAURANCE, 2009). Avoided Deforestation Partners could be targeted where they can provide most benefit at the country level, and could be used to tackle poverty reduction and underlying drivers of deforestation (WRM, 2007). Many developing countries believe that the global trade in pollution credits would deliver sufficient funding for effective Reduced Emissions from Deforestation (RED) schemes under UNFCCC. A mechanism should provide adequate financial resources to compensate countries for the economic benefits they lose by reducing deforestation. Many industrial-scale deforestations are done by multinational firms or domestic companies seeking access to international markets. Conservation groups would be able to mobilize public support for forest conservation through consumer boycotts and public-awareness campaigns (BUTLER and LAURANCE, 2009). The countries importing timber and wood products might establish and operate a system for denying market access to timber and wood products produced and exported illegally (BRACK *et al.*, 2002). Multinational corporations could enjoy the growing consumer preferences and premium prices for their eco-friendly forest products. Green forest products which are produced in an environmentally sustainable manner accounted for $7.4 billion in sales in the USA in 2005, and are expected to grow to $38 billion there by 2010 (BUTLER and LAURANCE, 2009). Recycling of throwaway timber products can reduce the demand for timber that has made illegal logging profitable (LARSEN, 2002).

Worldwide Imposition of Penalties on Illegally Timber Trade

If laws and standards are upheld, the Convention on International Trade in Endangered Species of wild fauna and flora can help to prevent illegal logs from crossing international borders. The European Parliament under a proposed EU regulation on February 18, 2009 has imposed stiff penalties on companies who use or trade illegally sourced timber (BUTLER, 2005). Establishment of internationally agreed standards which products would have to meet, independently verified chain-of-custody monitoring, would reduce market share for illegal timber and wood products. Reform of domestic laws and regulations dealing with forest crimes and related activities is an essential prerequisite for the successful implementation of the controlling illegal timber trade (BRACK *et al.*, 2002). The Government of New Zealand endorsed a set of recommendations in November 2006 to produce a declaration of conformity with the laws and regulations of the country of origin in order to combat illegal logging and associated trade (OGLE CONSULTING LTD., 2008). The Asia Pacific Group meeting held in Brunei in 2004 discussed the use of anti-money-laundering regimes to combat forestry crimes and promote sustainable forest management (SETIONO and HUSEIN, 2005).

Dialogues and Educational Campaigns on Scientific, Industrial and Conservational Interests

The forestry profession is recognized to be indispensable to continuously providing adequate condition of the sustainable forest management. Tropical forest conservation could be most effectively met through improving levels of international collaboration and by strengthening the capacity of the scientists in developing tropical countries. The community via particular measures and with an adequate expert support can preserve the forest and assist in its development. Forest education based on economic and environmental concerns would be a promising tool to stabilize natural forests through empowering communities. Education campaigns can increase public appreciation of the environment and spread awareness of environmental problems inducing more environmentally conscious behavior. Consumer-education campaigns targeting conservation interests and strategic forest-related industries would be able to slow harmful forest depletion (BUTLER and LAURANCE, 2009). Many countries, organizations, conferences and international initiatives have focused, balanced and sustainable forest management for the conservation and development of forest ecosystems. Growing public concerns about environmental sustainability are creating important new opportunities for combating tropical forest depletion. It has become a vital importance to reach an understanding on what sustainable forest management means and on its implications for conservation, development, protection and production. The forest protection can be accelerated by environmental education campaigns conducted by forest department, universities, schools, and NGOs.

Forestry Aiming for Food Security and Promote Multipurpose Forest Management

Recognition of the role of non-timber forest products in food security has grown considerably over the past decade. Forests play an important role in contributing to the food security of a large portion of developing countries (GBETNKOM, 2008). It has become a vital importance to consider the food security of lo-

cal people in developing and implementing forest management and agroforestry practices. Increasing the agricultural value added per hectare may increase the profitability of maintaining forests. Sustainable forest development requires a basis of technically appropriate, financially viable and socially acceptable methods. Forest management must systematically address the full range of issues as the local people need food, energy and social services to meet their basic needs. Forest industry has to find enough timber to remain viable in a competitive international market and grater forest areas must be grown to offset carbon emissions. Multipurpose forest management is a form of sustainable forest management and sustains the essential functions and components of the forest ecosystem. Multipurpose forestry approaches would broaden forest management interests and increase the amount of management effort per unit area from a narrow focus on timber benefits to include environmental and social considerations.

Establishment of Community Forest Governance

The sustainability of forest management is facing a challenge of balancing market demands, environmental concerns, wise use of resources and equitable sharing of benefits among stakeholders. Socio-economic and socio-political variables at the community level affect the ability of communities to cooperate with each other in conserving forests under forest governance regimes (KANT, 2000). Although the approaches to forest governance are becoming common, the knowledge with regard to how local people can participate effectively in forest governance policies and practices has to be promoted in developing countries. Forest governance has become a highly important strategy with a growing array of stakeholders, changing to multi-centric structures, and differences in scales, goals and means of forest management. Community-based forest governance would influence forest conditions in diverse ecological and institutional settings. The governance in community forestry has become a central concern to relationships between government agencies, forest communities, civil societies and intermediaries including NGOs working in forest management. Community governance would foster accountability and transparency of community forest management with equitable relations among all the partners including the government (MENZIES, 2004). Rights to become organized, entitlement over growing stock, right to use benefits and unalienable rights after withdrawal of the project would be significant incentives and motivation for local forest communities to participate in forest governance. Forest governance needs to take into account the biophysical variables that play a highly important role in shaping forest conditions so as not to overemphasize the role of socio-economic or institutional influences over forest condition.

CONCLUSIONS

The tropical regions in the world have already lost over two-thirds of their original forest cover mainly due to the intensification of agriculture and other economic activities and also illegal logging resulted with the land erosion and flooding, species extinction and global warming. A straightforward protected areas approach, market-based good forest management, integrated conservation and development programs, community forestry development, creating markets for ecosystem services and forest certification have been implemented or at least talked about to prevent forest depletion. Tropical forest depletion is still a reality with shifting socio-economic conditions and financial crisis, inappropriate community forestry, development and industrial activities, globalized financial markets, corruption and weak governance, and political influence on carbon trade. Global forces and local pressures confronting tropical forest conservation have to be addressed through international collaboration and partnerships, consumer-awareness campaigns, dialogue among industrial and scientific and conservation interests. Implementation of multipurpose forestry programs and establishment of community forest governance will be able not only to combat forest depletion but also to promote sustainable forest management. The current challenges to combat tropical forest depletion created by shifting drivers have to be address through flexible programs designed globally and locally appropriate to changing circumstances.

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Review

A Management Issue for Ecotourism in Taiwan's Forests: To Determine or to Manage the Tourism Carrying Capacity?

Wen-Pin Lin*

ABSTRACT

In Taiwan, the idea of ecotourism emerged in the 1980s when Taiwan's national parks began to provide educational tours and interpretation services for visitors. Since then, ecotourism has been a popular term for marketing tourism in national parks, forest stations, natural reserves and rural areas in Taiwan. The "Ecotourism White Paper" for Taiwan was completed by the National Council for Sustainable Development (NCSD) in 2004, in an attempt to provide more environmentally sound guidelines for ecotourism management. One of its key management strategies is to determine a "tourism carrying capacity" for each destination to prevent its environment from degradation. Therefore, it brings up the question of how the manager of an ecotourism destination can properly determine a carrying-capacity limit that would stand the test. To examine this issue, this paper briefly reviews some applications of tourism carrying capacity for forest recreation management in Taiwan, and then explores the inherent features of management problems in ecosystems as well as some strategies to deal with them. Lastly, the implications for the future applications of tourism carrying capacity in Taiwan's forests are discussed, and it ends in the conclusion that tourism carrying capacity should be tackled as a decision-making issue in ecosystem management. That is, tourism carrying capacity is a management action that should be evaluated over time, and it is not a fixed number to be determined.

Keywords: ecotourism, tourism carrying capacity, forest ecosystem

INTRODUCTION

Taiwan is a mountainous island and forests occupy almost two thirds of its total land area. According to the Third Survey of Forest Resources and Land Use in 1995, forestland occupied 2,102,400 ha, covering about 59% of the total island area (Forestry Bureau, Taiwan, 2009). In Taiwan, ecotourism emerged in the 1980s when national parks began to provide educational tours and interpretation services for visitors; and it was further advocated in the forest recreation areas and national trail systems managed by the Forestry Bureau (Tourism Bureau, Taiwan, 2002). This relatively new idea of tourism drew extensive attention of the public in 2002, when the United Nations and the Taiwan government proclaimed that year as the Year of Ecotourism. A variety of so called "eco-tours", offered by national parks, natural reserves and forest stations, were promoted in Taiwan's domestic travel market. The term "ecotourism" thus became a popular slogan for marketing tourism in these areas.

However, Taiwan's ecotourism faced a great deal of criticism at that time. The eco-tours in question introduced a large number of visitors to nature areas for specific faunal and floral attractions (e.g. giant Taiwan cypresses, fireflies, butterflies). Ecotourism in Taiwan was blamed for creating an even more severe impact than traditional tourism because the eco-tours invaded relatively undisturbed ecosystems or vulnerable habitats, such as virgin forests on Ta-hsueh Mountain. Consequently, it led to a call for Taiwan's government to take action to provide more environmentally sound guidelines for ecotourism management. This included replacing the Tourism Bureau with the National Council for Sustainable Development

Corresponding author: Wen-Pin Lin
E-mail: wenpin@hotmail.com
* Department of Tourism and Leisure Management, Ling Tung University, No.1 Ling Tung Road, Taichung, Taiwan/ROC

(NCSD) as the administrative organization of ecotourism management and revising the Ecotourism White Paper (originally composed by TOURISM BUREAU in 2002). The new version of the Ecotourism White Paper for Taiwan was then completed by the NCSD in 2005. This transition implies that the ecotourism management in Taiwan has placed more emphasis on conservation and sustainability than on tourism promotion.

One of the key management strategies proposed by the NCSD version of Ecotourism White Paper is to determine a carrying capacity for each ecotourism destination to prevent both its ecosystem and recreational environment from degradation (NCSD, 2005). Carrying capacity is not a new concept for forest recreation management in Taiwan. In fact, some of the forest recreation areas have applied this concept in their management polices since the 1990s. One of the most famous examples, Fu-Shan Botanical Garden, located in the mountain areas in the northeastern part of Taiwan, has implemented a carrying-capacity policy since 1993 (LIN and DONG, 1996). It not only sets a daily maximum number of tourists allowed to enter the garden, but also limits the areas and times of visiting. Nowadays, many ecotourism destinations in national parks and trail systems have complied with the carrying-capacity policy in an attempt to control or mitigate the environmental impact of visitors to some degree.

Despite this not being a new concept, it raises the old debate of whether or not a carrying capacity for an ecosystem is even calculable. It is commonly agreed that carrying capacity is not a fixed or absolute number and it can be viewed as a variable depending on management objectives, technological innovation, and social values (MITCHELL, 1997). However, the discussion about this debate is not the focus of this paper. Rather, it is intended to discuss the question of how the manager of an ecotourism destination can properly determine a carrying-capacity limit that would stand the test. To examine this issue, this paper briefly reviews some applications of tourism carrying capacity for forest recreation management in Taiwan, and then explores the inherent features of management problems in ecosystems as well as some strategies to deal with them. Finally, the implication for future application of tourism carrying capacity in Taiwan's forests is discussed.

APPLICATIONS OF TOURISM CARRYING CAPACITY FOR FOREST RECREATION MANAGEMENT IN TAIWAN

In Taiwan, research on tourism carrying capacity for forest recreation management can be traced back to the 1980s. Among those important applications is the research conducted by LIN (1987). It was intended to analyze the recreational carrying capacity for Yu-Shan national park, focusing on two key management issues for the national park. First, the social carrying capacity for camping areas and accommodation facilities was analyzed using the perceived crowding model. The second issue is concerned with the physical-ecological carrying capacity for trails and camping areas in Yu-shan National Park. Due to the lack of empirical data about the relationship between recreational activities and environmental responses, the research evaluated the physical-ecological carrying capacity based on experts' subjective judgments derived from the analytic hierarchy process (AHP).

CHIEN and YANG (1992) took a different approach to assessing the physical and ecological carrying capacity for trails and barbecue areas on Four Beast Mountain in Taipei. They developed regression models describing the relationship between the number of visitors, activity intensity and the vegetation destruction (soil exposure) on trails and barbecue areas, and then applied the concept of the limits of acceptable change (LAC) theory to assess the maximum number of visitors allowed per week and establish a land-use policy. Although this study still had to rely on subjective judgments, it analyzed the physical-ecological capacity in a more objective way by using empirical data. A similar approach is applied in the evaluation of ecological capacity for a scenic area of Kenting National Park, in which the ant abundance index was used as the key evaluating factor of the ecological carrying capacity (YEN, 2004).

In practice, the carrying capacity for an ecotourism destination in Taiwan is often determined without a sound theoretical basis. Fu-Shan Botanical Garden is one of the pioneers that carry out a strict policy of tourism carrying capacity. In 1993, about 30 hectares of the area was open to the public, and the visitor limit was 300 persons per day. This number was determined based on a simple assumption that 10 visitors per hectare was the "reasonable" number that would cause the least environmental impact, taking into account the consideration of facility capacity, such as the total area of the parking lot and the mode of transportation (LIN and DONG, 1996). However, this famous ecotourism destination has been under the pressure of increasing demand. Consequently the daily visitor limit was increased to 500 persons during the week and 600 on holidays (FUSHAN RESEARCH CENTER, 2009). A similar rationale has been applied in the determination of the maximum number of 400-500 visitors allowed daily to enter Kueishan Island (or, Turtle Island), where most of the area is covered by natural forests (NORTHEAST AND YILAN COAST NATIONAL SCENIC AREA ADMINISTRATION, 2007). MA *et al.* (2003) suggest that the turnover of visitors should be the deciding criteria in making a more reasonable estimation of carrying capacity for Kueishan Island.

STRATEGIES FOR DECISION MAKING IN FOREST ECOSYSTEM MANAGEMENT

Inherent Features of Management Problems in Ecosystems

In practice, we have very limited knowledge in accurately and completely predicting ecological contingencies and assessing their impact on human life. Thus, HAYNES *et al.* (1998) identify four basic scientific principles guiding the process of ecosystem management:

- Ecosystems are dynamic;

- Ecosystems can be viewed spatially and temporally within hierarchical levels;
- There are limits to their ability to withstand change;
- There are limits to our ability to predict how ecosystems may change.

These principles suggest that resilience and uncertainty are two fundamental problems involved in the management of ecosystems. Therefore, exposing an ecosystem to ecotourism may have to face three situations: (1) some possible impacts cannot be predicted over a short-term time frame; (2) one or more of the consequences may have extremely adverse impacts for future people; and (3) there is no substitute available for the resource to be used. As a result, an effective management system should have the flexibility to deal with changing conditions, uncertainty or ignorance. This makes the so-called "precautionary principle" (MITCHELL, 1997), which stresses the need for caution or foresight in planning and management process, a worthy approach to ecotourism management. MITCHELL (1997) points out that a precautionary strategy tends to suggest that at least the present physical and biological productivity of ecosystems should be maintained.

Adaptive Management

The approach of adaptive management, featuring "learning by doing" (WALTERS and HOLLING, 1990; cited in HANEY and POWER, 1996), has also been advocated by many authors as a necessary process to account for the uncertainty inherent in ecosystem management since the 1970s (MCLAIN and LEE, 1996). Rather than trying to eliminate the uncertainty, it focuses on developing more resilient policies and designing management processes that allow trial-and-error procedures to work (HOLLING, 1978, cited in MITCHELL, 1997). Adaptive management is an approach to natural resource policy that embodies a simple imperative: "policies are experiments; learn from them" (LEE, 1993, p.9). That is, it is an approach which treats management as an adaptive learning process, where management activities themselves are viewed as the primary tools for experimentation (WALTERS, 1986). It can also be regarded as a policy framework that allows iterative decisions to be made based on the best information available, and also allows decisions to be revised as new information/knowledge is collected and learned (WIERINGA and MORTON, 1996). Proponents assert that this approach increases knowledge acquisition rates, enhances information flow and provides opportunities for creating shared understandings among stakeholders (MCLAIN and LEE, 1996). However, this approach may not comply with the "precautionary principle" , because some "trials" are too risky or some "errors" in ecosystems are just not allowed to happen.

Robustness Analysis

Robustness analysis is regarded as an approach to problem situations in which uncertainty is high, and where decisions must be made sequentially. It is aimed at increasing the "flexibility" of decisions against a high degree of uncertainty and intended to be distinguished from the "seeking-for-optimal-solution" approach (ROSENHEAD, 1980). The main task of this approach is to identify an initial decision package (initial management activities) and alternative future states of the system. The robustness of a decision can be expressed as the following mathematical notation:

$$\boldsymbol{r}_{ij} = n(S_{ij})/n(S_j)$$

where,

$\boldsymbol{r}_{ij}$ = the robustness of a initial decision i in future j (the value of $\boldsymbol{r}$ is between 0 and 1)

$n(S_{ij})$ = the number of acceptable options consistent with decision i under future j

$n(S_j)$ = the number of all acceptable options under future j

$\boldsymbol{r}_{ij}$ can be expressed as a two-dimensional matrix (decision × future), called the Multi-Future Robustness Matrix. On the other hand, a contrastive matrix, Debility matrix, can be also constructed through the same methodology described above. Debility is defined as the number of unsatisfactory end-states still attainable after an initial decision. Decisions thus are analyzed and evaluated by comparing these two matrixes. For example, a management decision is preferred if its robustness scores are high and debility scores are low. It needs to be noted that this approach doesn't intend to assess the absolute degree of flexibility for alternatives. The acceptability of options and the possible futures are determined by decision-makers under consistent conditions.

Alternative Strategies: Toward an Integrated Approach

As pointed out by PRATO (2000), the implementation of adaptive ecosystem management is hampered by the lack of a framework to identify management actions. Therefore, he proposes a two-stage hierarchical framework for adaptive ecosystem management. The first stage uses Bayes rules to identify management actions that have the greatest likelihood of achieving a sustainable ecosystem state, in terms of ecological productive capacity. The second stage evaluates the sustainable state based on other non-ecological attributes. Although the probability approach is often questioned in dealing with ecosystem-management problems, the framework proposed by PRATO (2000) provides a strategy for the implementation problem of adaptive management.

LIN (2006) proposed a framework integrating the process of adaptive ecosystem management and robustness analysis. The purpose is to conduct robustness analysis on initial decisions against multiple futures and eventually to identify a plan of carrying capacity for implementation. It is intended to synthesize the strength underlined in the approaches discussed previously. However, a couple of application issues are also identified to be addressed in further studies. First, it is necessary to identify threshold levels for acceptable options in robust-

ness analysis. To incorporate the precautionary principle into the analysis process, the condition in which the present physical and biological quality of ecosystems is maintained can be regarded as a key criterion.

CONCLUSION

This paper is not intended to discuss the theoretical background of carrying capacity, nor the pros and cons of various strategies for decision making in ecosystem management. Rather, it attempts to ponder how the related strategies can contribute to the decision-making process for tourism carrying capacity and the implications for future application in Taiwan's forests. Indeed, as mentioned previously, carrying capacity should not be regarded as an absolute number; however, the ecotourism policy in Taiwan has forced forest managers to determine a fixed limit of visitors. As a result, this paper asserts that a better way to handle this problem is to deal with tourism carrying capacity as a decision-making issue in ecosystem management. Furthermore, tourism carrying capacity is a management action that should be evaluated over time, and it is not a fixed number to be determined. The analysis of pitfalls of the implementation of a single strategy suggests that an integrated approach synthesizing the strength underlined in different approaches can be more promising. Nevertheless, any proposed approach is needed to be applied in a real-world problem to evaluate its applicability; and it may also need to consider whether the organizational environment of ecotourism management in Taiwan is amenable to, or not antagonistic towards, any form of management framework.

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Article

Information and Communication Technology Connecting Mathematical Modelling with Multipurpose Forest Management

Tuula Nuutinen[*1,2], Aimo Anola-Pukkila[*2], Hannu Hirvelä[*3], Leena Kärkkäinen[*2] and Helena Mäkelä[*3]

ABSTRACT

Forestry is facing new challenges due to, e.g. multiple needs and values of people and society, globalisation of markets and changing climate. To safeguard the benefits to current and future generations, governments have applied different means of regulation. In global markets, individual market players, such as forest owners, companies and consumers, seek their own benefits. Sometimes conflicts appear between governing and market behaviour. To close this gap, there is a shift towards new governance emphasising voluntary, community and market-based instruments such as certification, community forests or commercial values for ecosystem products and services. Consequently, there is a need for decision support for market players, such as forest owners, and policy support for governmental consumers of ecosystem products and services. Luckily, recent advances in science and technology make it possible to support complicated decision- and policymaking situations. The aim of this study was to illustrate how information and communication technology helps to connect mathematical modelling with multipurpose forest management. First, the methodology and implementation of the Finnish MELA system are presented as an example of knowledge transfer in practical forestry. Thereafter, a case study is used to illustrate how MELA can be linked with multisource national forest inventory (MS-NFI) data, a geographic information system (GIS) and web-based services to facilitate collaborative planning and social learning in the context of a local forestry programme.

Keywords: governance, collaborative planning, knowledge transfer, local forestry programme, multisource forest inventory

INTRODUCTION

Forestry is facing new challenges due to, e.g. globalisation and consequent requirements for improvements in cost-efficiency, which needs to be balanced with the multiple needs of people and society. Enterprises responsible for wood procurement seek cost-efficiency via logistics, for which they request real-time forest resource data. For their own forests, forest owners seek feasible and effective combinations of forest ecosystem services and products with subsequent forest operations. Effectiveness is dependent on owners' own forest resources and objectives as well as on the available technology. Feasibility is limited, e.g. by surrounding regulation and markets for products and services. With regulation and related monitoring, governments safeguard sustainability for current and future generations.

Sometimes government regulation conflicts with the interests of forest enterprises and forest owners. To close this gap, there is a shift towards new governance in forestry that em-

Corresponding author: Tuula Nuutinen
E-mail: tuula.nuutinen@metla.fi
[*1] European Forest Institute, Joensuu Torikatu 34, FI-80100 Joensuu, Finland
[*2] The Finnish Forest Research Institute, Joensuu Yliopistokatu 6, P.O. Box 68, FI-80101 Joensuu, Finland
[*3] The Finnish Forest Research Institute, Vantaa Jokiniemenkuja 1, P.O. Box 18, FI-01301 Vantaa, Finland

phasises voluntary, community and market-based instruments such as certification, community forests and markets for ecosystem products and services (Howlett *et al.*, 2009). The traditional approach based on land-use segregation and zoning for different purposes is being replaced by joint production of timber and other products and services (e.g. Forest Biodiversity Programme for Finland, 2009). Commercialisation of different types of ecosystem products and services (such as emissions trading, trading of nature and recreational values or renting landscape), however, creates new challenges – especially for forest owners. For example, the utilisation of new opportunities may require new ways of neighbourhood co-operation as well as collaborative commercialisation, marketing and social networking. Obviously, the market players need decision support and governmental customers of ecosystem products and services need policy support.

Globally, the most recent challenges in forest management are related to the relationship between rural communities and forestry. In rural areas, forests are an important part of the living environment and forestry is a part of livelihood. Furthermore, rural communities play a role in forestry and forest management. Moreover, rural areas are an important source of raw material and work force. Therefore, balancing livelihoods based on forestry and other (non-commercial) forest uses is increasingly important for rural communities.

Recent advances in science and technology make it possible to support complicated decision- and policymaking situations. For example, so-called multisource inventory based on satellite imagery and intensive field measurements (see Tomppo *et al.*, 2008), which rapidly covers large areas, is applicable for monitoring and strategic planning purposes from the global to the local level. Remote sensing techniques with higher resolution (e.g. digital aerial photographs and laser-scanning from an aeroplane) have been successfully integrated with field measurements to produce detailed data for decision-making (Packalén, 2009). Furthermore, computerised tools can be used to integrate the results from monitoring systems with scientific knowledge. To support decision- and policymaking, the flow of costs and benefits in different future scenarios can be studied using mathematical models incorporated into forest information systems (von Gadow *et al.*, 2007). The role of these models is to support exploration of management options and their bio-economic consequences.

In Finland, forest management planning at the company, forestry-unit or forest-estate level is based on standwise forest inventory. In forest companies and in Metsähallitus (organisation responsible for state forests in Finland), stand data are stored in real-time forest information systems and kept up-to-date when changes are detected. For non-industrial private forests (NIPF), comprehensive and homogenous forest data are collected periodically (traditionally at interval of 10–15 years).

Individual forest owners make their own decisions concerning cutting and silvicultural operations, which consequently affect the supply of timber and forest conditions for all citizens. Most of the Finnish forests (about 12 mill. hectares of forest land) are owned by NIPF owners (Finnish Forest Research Institute, 2008). Since World War II, forestry and the forest industry have played an important role in the Finnish national economy. Therefore, different policy measures have been defined in order to encourage intensive utilisation and management of private forests to provide raw material for the forest industry on both a short- and long-term basis. Policy measures include national forest programmes (Finland's National Forest Programme 2015, 2008) co-ordinated by the Ministry of Agriculture and Forestry as well as regional forest programmes and property-level forest planning for NIPF carried out by regional forestry centres.

In addition to data collection and planning services by the regional forestry centres, forest owners also have access to a wider selection of services. For example, forest management associations, forest companies and various forest service providers offer tools for planning of forest operations based on real-time forest information services.

In Finland, forest programmes at the national and regional levels are prepared by using an interactive (participatory) process involving different interest groups (Finland's National Forest Programme 2015, 2008). Forest programmes cover forests in all ownership categories (non-industrial private, company, state and others) and have been supported by calculations based on sample plot and tree data from the Finnish National Forest Inventory (NFI). Metsähallitus has also utilised an interactive process in the preparation of both landscape ecological plans and operational cutting plans for state forests. All these processes are based on the analysis and evaluation of different scenarios or plan alternatives. However, very little attention has been paid to collaborative planning at the local (community or village) level.

The aim of this study was to illustrate how information and communication technology helps to connect mathematical modelling with multipurpose forest management. First, methodology and implementation of the Finnish MELA system (MELA originates from the Finnish word MEtsäLAskelma, i.e. forestry analysis, see Siitonen *et al.*, 1996) is presented as an example of knowledge transfer to practical forestry. Thereafter, a case study is used to illustrate how MELA can be linked with multisource national forest inventory (MS-NFI) data, a geographic information system (GIS) and web-based services to facilitate collaborative planning and social learning in the context of a local forestry programme.

METHODOLOGY

Management practices are continuously improved based on science and monitoring of the forest and its environment (von Gadow *et al.*, 2007). Since the 1980s, decision-support systems have become popular platforms for transferring scientific knowledge and technology to analyses of different forest management alternatives and their impacts.

In the beginning, systems were often used by researchers themselves for case studies and demonstrations. Further development of these systems was initiated by new research questions or new scientific or technological knowledge. The benefit for end-users depended on how well the case studies and demonstrations corresponded to their own decision-making situation. Therefore, the demand for tools with tailored user-interface and data-interface increased. To fulfil this demand, some customer-oriented software tools were developed. Gradually, the use of software tools integrated with users' own forest data became popular and made decision-making in practice more analytic and rational. However, the maintenance and further development of software systems became more challenging for the research community. Firstly, end-users started to request features (e.g. graphical user-interface) that were more related to computer technology than to forest science. Secondly, the export of new research results to dozens of user-specific software versions became time consuming. Software engineering started to require more skills and human resources.

For example, the Finnish MELA system was designed in the 1970s for analyses of regional and national timber production in Finland based on NFI sample plot and tree data (SIITONEN, 1993). Since the 1980s MELA has been used widely as a module in forest information systems for companies, state forests and private forestry. In 1996, the software was commercialised, and the maintenance and development of the system were re-organized by the MELA Team of the Finnish Forest Research Institute. The current outputs include the MELA software and a set of internet-based services such as DemoMELA (NUUTINEN *et al.*, 2006a), NettiMELA and MELA Analysis Service (METINFO, 2009). Internet-based dissemination makes knowledge transfer to practice easier and faster.

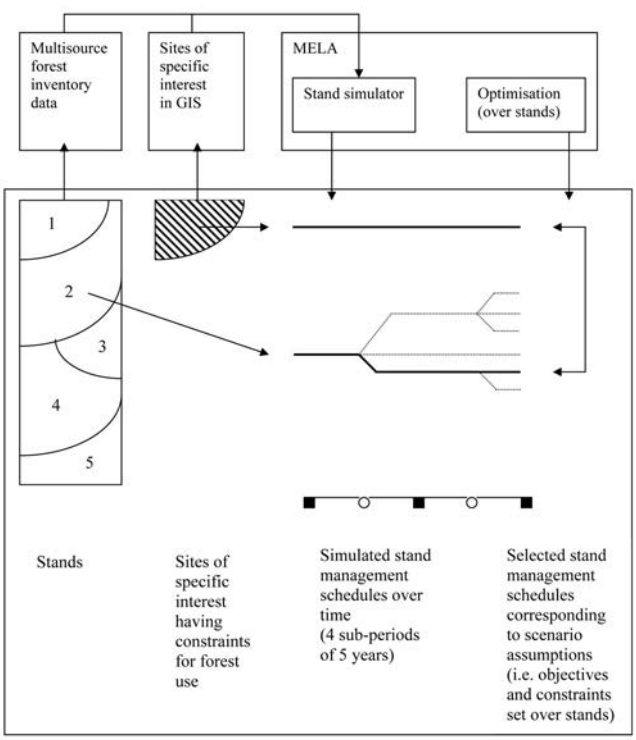

Fig. 1 The principle of the MELA System and its implementation

The MELA system has two main components: a stand simulator and an optimisation package (Fig. 1). The system was developed for conditions where most stands usually have, at any point in time, more than one option for management operations. Therefore, a stand simulator automatically generates feasible alternative management schedules (over time) for management units, such as forest stands or sample plots representing the stands, and for each management schedule calculates hundreds of variables. The options for individual stands may be limited because of site-specific land-use or forest-use constraints.

In the simulation, users can control, e.g. management activities, prices and costs. The scenario period is divided into sub-periods, for which, both at the beginning and end of each sub-period, so-called state variables are calculated to describe standing trees and their environmental conditions within the stand. In the middle of each sub-period, so-called change variables describing management activities (e.g. harvested trees, costs and incomes) are calculated. All state and flow variables can be included into an optimisation package for the calculation of regional scenarios. In the optimisation, objectives and constraints corresponding to defined scenarios are defined by the user. The optimisation package seeks a combination of management schedules that corresponds to the values given as scenario assumptions concerning management and development of forest resources at the regional level. All the state and change variables are available for reporting the scenario at the regional, management-unit and tree levels.

To assist the preparation of regional and national forest programmes, the Finnish MELA system has been used to analyse possibilities for future (typically the next 30-50 years) forest production and utilisation (e.g. NUUTINEN *et al.*, 2000; NUUTINEN *et al.*, 2006b; NUUTINEN *et al.*, 2009). The alternative MELA scenarios are based on the NFI sample-plot and tree data. The sparse sample of NFI is not applicable for the analysis of regions smaller than forestry centres. However, integration of MELA with the satellite-based multisource NFI (MS-NFI) (TOMPPO *et al.*, 2008) and GIS opens up new possibilities for analysis at the local level, e.g. at village level. Furthermore, web-based services can be used to disseminate the results for a wider audience.

CASE STUDY

Background

The local forestry programme for Koli and Hattusaari (NUUTINEN *et al.*, 2007) villages presents the objectives of the two-village community for development of the use of forest

resources during the next ten years and examines strategies for sustainable use and opportunities for development of the forest resources of the whole area. In addition, it also includes a description of the current status of the forests and identifies sources of financing for community initiatives. It is the first forest programme prepared at such a local level in Finland.

The local forestry programme was drawn up as a part of the international, three-year ELAV project (Enhancing Local Activity and Values from Forest Land through community-led strategic planning). The aim of the project was to examine opportunities offered by the forests for development of the rural economy and improvement of the vitality of the area. The project was funded by the European Union, the Interreg IIIB Northern Periphery programme of the European Regional Development Fund, with participation of forest organizations from Finland, Sweden, Norway, Iceland and Scotland. Further funding for the Finnish section of the project was obtained from the Finnish Ministry of Agriculture and Forestry.

Study Area

The study area is located in the province of North Karelia in eastern Finland (Fig. 2). The total area was 11,375 ha, of which the area of forest, scrub and waste land was ca. 9820 ha (Nuutinen *et al.*, 2007). In Koli and Hattusaari, the number of inhabitants is ca. 300. The proportion of primary production of the workplaces is 16 %, secondary production 8 % and services 76 % (Statistics Finland, 2006). Many kinds of associations and organisations dealing with, e.g. nature, culture, sport or hunting, are functioning in the villages (Nuutinen *et al.*, 2007).

Annually, 100,000–120,000 people visit Koli National Park, which is important for protecting the national landscape. In this national park there are, e.g. precipices, old-growth forests and grass-herb forests in the national park. Several nationally and regionally endangered plant and animal species can be found there. An important way to use forests in the area of Koli and Hattusaari is picking berries and mushrooms. Hunting is also a common hobby in that area, the most important game animal, economically, being elk (Amer. Moose, *Alces Alces*). Elk cause damage in seedling and sapling stands; thus it is important to limit the number of animals. In the area of Koli and Hattusaari, the old-growth forests are interesting places for bird-watching. In this area there are three areas belonging to the Natura2000 network: Koli National Park, Verkkovaara and Iso-Veteläinen. (Nuutinen *et al.*, 2007)

During the last 15 years, many plans have been formulated for the area of Koli and Hattusaari. The Union of Rural Education and Culture prepared a development plan for the village of Koli. In that plan, the ideas of the village people for the development were, e.g. co-operation between entrepreneurs operating in the same field, education of guides and co-operation between organisers of different events (Koli Village Futures Workshop, 1993). The long-term plan for the development of tourism, Koli Master Plan, was completed in 2007 (Koli Master Plan, 2007). The Ministry of the Environment ratified the management and use plan for Koli National Park

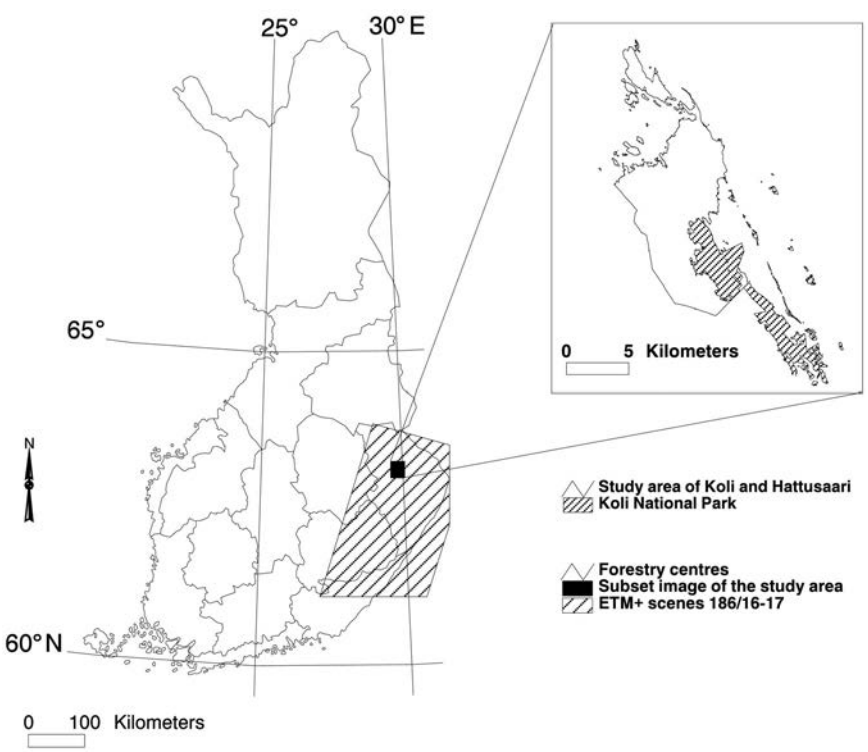

Fig. 2 Location of the study area

in 2004 (Koli National Park 2010, 2005). The regional land-use plan also sets some restrictions for the use of land. For example, ground-water areas, nature-conservation areas, areas for developing the use of shores and the most important trails are included in this plan. There are three local master plans and 17 local detailed plans (shore plans) in Koli and Hattusaari area (Technical Services Centre of Lieksa, 2007).

Implementation of the Case Study

The aim of the process (Fig. 3) leading to the programme was to identify the opportunities offered by the forests that could provide a basis for development of local livelihoods and enhance the vitality of this rural area. The forestry programme was prepared at the village level, in the form of a local working group composed of village inhabitants. Additional support for the work of the group came from public events and international exchange visits. The interactive sessions at the core of the process included two field trips, two forest sessions and a forest planning day.

A description of the current status of the two-village area utilized local expertise, statistical data, previous plans and reports, land-use regulations and maps, specialists in different areas, and current information taken from the Internet, which was provided by different organizations.

The Finnish Forest Research Institute (Metla) facilitated interactive processes with the working group and other local interest groups (sub-process 1, Fig. 3). Scenarios as well as indicators used in their evaluation were defined by a local working group (sub-process 2). The indicators describing the commercial use of wood resources were volume of cutting removal, volume of cutting reserve and biomass of energy wood in spruce-dominated stands. The cutting reserve means growing stock, which could have been cut according to the recommendations, but in the scenario was not selected to be cut. The biomass components of energy wood were tops of stems, branches, foliage, stumps and roots. The indicators for the other values of the forests were area by dominant tree species and age classes, volume of growing stock by age classes and area of cuttings. Jobs were described using number of working days for forestry work and for work related to other values of forests. The number of working days in forestry work was estimated for intermediate cuttings and regeneration cuttings. The effect of different scenarios on the number of working days for work dealing with other values of forests was estimated based on the other indicators.

Scenarios for the use and development of the forest resources were calculated using the MELA2005 (Redsven *et al.*, 2005) system for simulations, MS-NFI data for the representation of forest resources and a GIS for incorporating land-use and land-cover constraints affecting forest management (sub-process 3). The values of the indicators in different scenarios were presented via web service (Fig. 4) to support evaluation by different local interest groups (sub-process 4).

The Regional Forestry Centre of North Karelia (acronym RFC, *Metsäkeskus Pohjois-Karjala*) and the Forest Management

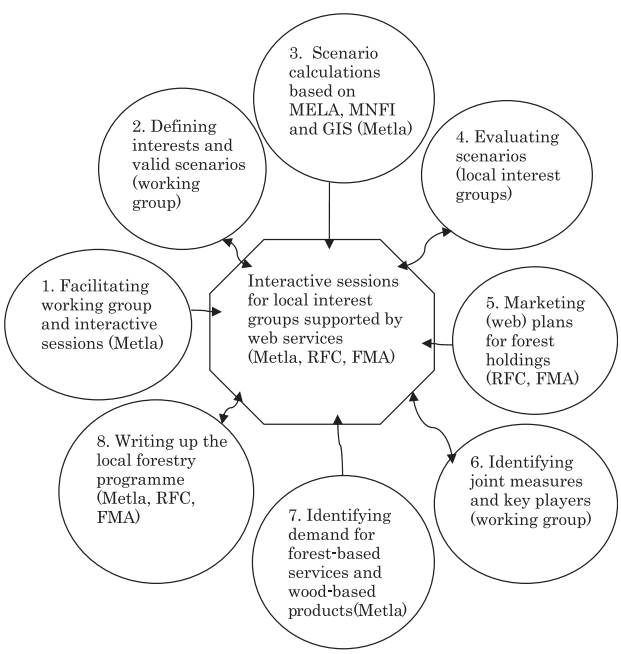

Fig. 3 The process of the local forestry programme consisting of eight sub-processes, linked with interactive sessions for local interest groups and supported by web services
(Metla=Finnish Forest Research Institute, RFC=Regional Forestry Center, FMA=Forest Management Association, MNFI=multisource national forest inventory)

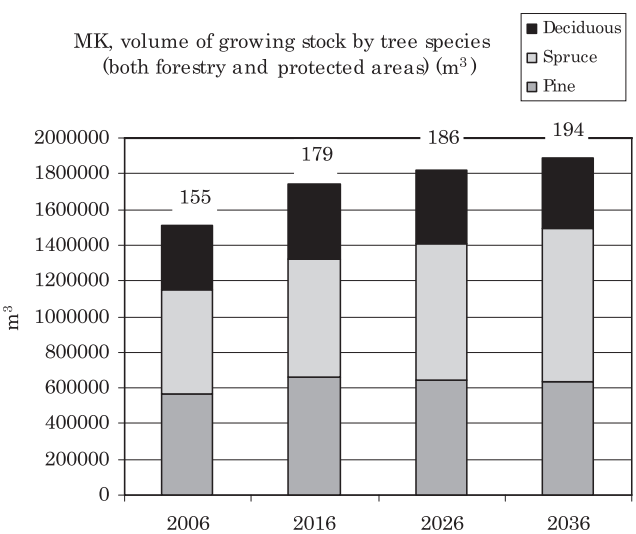

Fig. 4 An example of scenario output in the web service
The chart presented development of one indicator (growing stock by tree species, m^3 in bars and m^3/ha in numbers above the bars) for one scenario (MK) over time. In the web service 10 different variables for three different scenarios were presented.

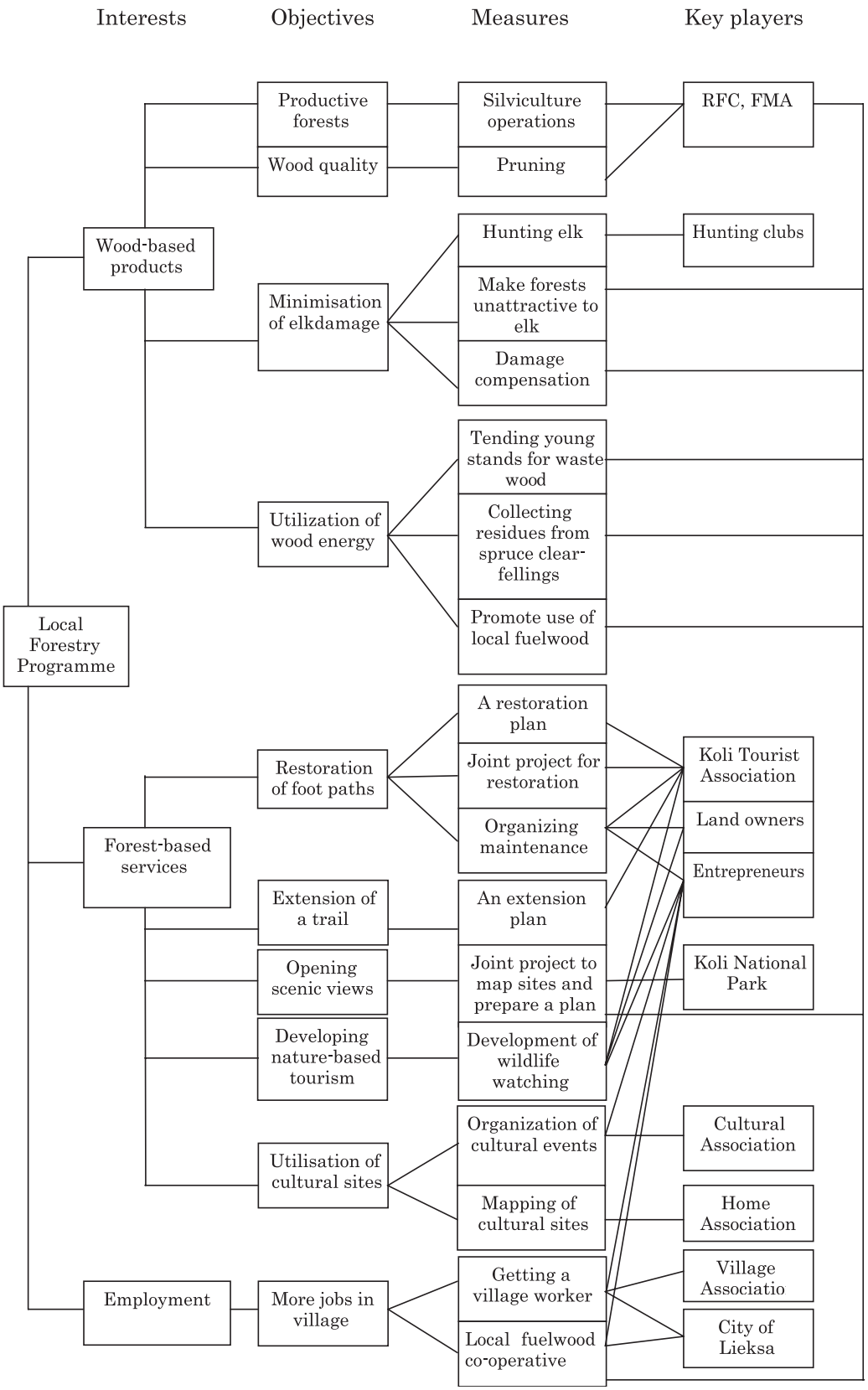

Fig. 5 Hierarchy of interests, objectives, measures and key players stated in the local forestry programme

Association of North Karelia (acronym FMA, *Metsänhoitoyhdistys Pohjois-Karjala*) supported forest owners during the process by compiling forest plans for forest owners and their holdings. A specific forest-planning day was organised in order to promote forest planning and especially web-based plans (sub-process 5).

Based on evaluation of the scenarios, the working group identified the measures and key players needed to achieve the objectives (sub-process 6). To support the implementation, Metla compiled information on possible sources of financing (sub-process 7). The process and its results were reported in the local forestry programme (sub-process 8).

Results

The most important result was the list of measures and key players corresponding to the objectives and interests of the local community (Fig. 5). The objectives related to the **commercial use of the wood resources** and **developing their use also as fuel** included: having productive forests, improving wood quality, increasing the amount of fuelwood harvested and used, and reducing damage caused by elk and utilising compensation for this damage. RFC and FMA were regarded as important players in reaching these goals. The necessary measures for meeting these objectives were identified as performing silvicultural operations in unmanaged seedling and sapling stands, correctly scheduling silvicultural treatments, increasing the level of pruning, harvesting fuelwood from unmanaged thinning stands and also from regeneration cuttings of spruce-dominated stands, increasing the use of fuelwood, and preventing tree damage by elk. The members of the working group especially wished for more training and guidance to be given to forest owners, in particular, targeted to aiding owners in identifying possibilities for financial support for silvicultural measures.

The objectives **related to other values of forests** for the programme identified by the working group included: restoration and maintenance of existing footpaths outside of Koli National Park, implementation of an extension to Herajärvi Trail, opening scenic views at important sites, developing the content of nature-based tourist services, and increasing the utilisation of the summer theatre venue and other places of cultural value. The working group regarded cooperation between different operators and organizations as important for achieving these objectives. Funding for future projects should come from regional sources, such as the Employment and Economic Development Centre of North Karelia (*Työvoima- ja elinkeinokeskus*), or through development programmes for rural areas, such as the European Union-funded Leader Programme for Vaara-Karjala.

Objectives related to **employment** stressed the need for more jobs. Measures listed in the programme to meet this goal were hiring a special village forest worker and support for creating a local fuel-wood cooperative.

DISCUSSION

The local forestry programme establishes measures that are highlighted or actively pursued by the community. The programme can also be used as a supporting document, when funding is sought for local development projects. In addition, the programme offers a tool for analysing the views of the local community on the use of forest resources in the preparation for regional and national forest programmes, as well as regional plans. A broader benefit of this pilot project is that the methods that have emerged as a by-product can be further utilized in other rural areas, where the coexistence of forest-based livelihoods with other uses of forests is found to be challenging.

The study integrated two different planning processes. In the first, a local forestry programme was prepared in an interactive and collaborative process. Simultaneously with the interactive and collaborative strategic planning at village level, decision support was produced and offered for individual forest owners in the form of forest management plans and personal assistance so that they would have information about the different possibilities for production in and utilisation of their own forests. Strategic planning methods applied in the project will have an impact on planning processes elsewhere in Finland since this project was the first of its kind at village or community level and has already awakened interest at regional, national and international levels.

This case study showed that information and communication technology (ICT) is essential in the facilitation of interaction, social learning, collaborative planning and networking. Firstly, the incorporation of MS-NFI data and GIS-based constraints for forest management provided relevance for discussions. Secondly, simulation tools created added value to data via impact assessment of scenarios in terms of criteria and indicators selected by a local working group. In addition, ICT tools such as a web-based analysis service were utilized in the visualisation and communication of scenarios.

In this process the role of expert organisations was that of facilitator. These organisations supported interaction, social learning, collaborative planning and networking. In the process, local inhabitants played a leading role, initiating forest management as a tool for improved wood production and quality as well as enhancing the potential for ecosystem services. They considered the role of forests and trees to be important in the mitigation of climate change. For example, they suggested forest management as a means to enhance tree growth and subsequently to increase carbon sequestration. As a by-product of forest management, they suggested that fuelwood should be collected to replace non-renewable sources of energy. Furthermore, they emphasised the importance of growing wood of good quality to be used later for making wood products with a long life-cycle.

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Article

Forest Resources Management to Support the Japan's "Culture of Wood"

Hirokazu Yamamoto*

ABSTRACT

Timber-frame building is a symbol of Japan's "Culture of wood" which makes use of renewable natural resources for construction. We face the global issue of limited natural resources, it is to this Japanese tradition of timber-frame building that we should turn to in to guide us to an important future course. 90 percent of cultural buildings designated by Japanese government are made of wood. The purpose of this paper is to estimate total material amount for timber cultural buildings and the forest resources needed to maintain wooden cultural assets and to propose social systems in order to secure forest resource for long-term more than one hundred years. About 40 percent of building parts are commonly replaced and at times requiring complete dismantlement. Total material amount of timber cultural buildings for government-designated structures was estimated approximately 300,000 m^3, annually a volume of 2,220 m^3 in standing trees was needed to secure 600 m^3 of repair materials. The average amount of wood used per square meter in timber-framed cultural buildings is on the order of 0.5 m^3. This means that these structures fix about 10 times the carbon as ordinary forest. For society as a whole to support the maintenance of cultural assets, it is necessary to disperse these risks as much as possible. Additionally, technical support measures are needed for forest owners to grow high-quality, large-diameter trees, and measures are needed to effectively use and raise the market value of timber that is produced but is not suitable for cultural asset repairs. That makes it necessary to increase the building of large-dimensional timber structures using large-diameter timbers, thereby inducing change in the manner of timber construction so that large-diameter timbers are primary. This will make it possible to log plantation trees at larger diameters and provide for longer rotation cycles.

Keywords: culture of wood, forest resources management, timber-framed cultural building, large scale timber

INTRODUCTION

The diverse functions of forests are regarded positively: In addition to conserving the land and recharging aquifers, they have "cultural functions" (Science Council of Japan, 2001). Yet, these cultural functions are insufficiently analyzed. While the spiritual influence on people living in the present has been researched, it would be hard to say that the cultural value of forests across vast expanses of time has been sufficiently assessed. In other words, there is insufficient analysis of the fact that forests formed in a warm and moist climate produce trees of excellent quality, which have over many years become the materials for cultural structures. Indeed, what kind of forests supplied the materials for the buildings constructed in the Asuka and Nara periods (7th and 8th centuries)? Where and to what extent do such forests still exist in Japan? We do not have enough information to adequately answer such questions. I want to find out how much material is needed, and what kind of forests must be maintained, in order to maintain valuable cultural properties. Showing the specific tree species and standards that are considered necessary to maintain cultural properties would be a valuable source of information for locating wood from forests all over Japan for cultural asset repairs. In this paper, I estimated the total material amount for timber cultural buildings and the forest resources needed to maintain wooden cultural assets using examples of the Ise Shrine and domestic repairing reports, and then I proposed

Corresponding author: Hirokazu Yamamoto
E-mail: yama@k.u-tokyo.ac.jp
* Graduate School of Frontier Sciences, the University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba, 277-8563, Japan

social systems in order to secure forest resource for long-term more than one hundred years.

Ninety percent of Japan's important cultural structures are wooden (EZURA, 2000), and nearly half of them have roofs covered with plant-based materials. These timber buildings and buildings with plant-based roofing materials cannot avoid weathering and rotting due to wind and rain, and each building needs periodic repairs. Currently, at least 240 timber cultural properties all over Japan are repaired annually (EZURA, 2000). These repairs are essential for cultural asset preservation, and will need to continue long into the future. They require high-quality lumber and plant-based materials. However, owing to changes in social circumstances and the economic situation in recent years, there has been a precipitous decrease in the domestic production of large-diameter wood, high-quality wood, and hardwood trees such as *Zelkova serrata* and Japanese chestnut (*Castanea crenata*), which are essential for repairs to cultural property structures, making it urgent to secure a stable supply of repair materials for cultural property structures. A questionnaire survey of cultural asset repair technicians found that 80% of them have at some time been unable to obtain the needed materials and have substituted something else (EZURA, 2000). They report that this situation has been pronounced for about 30 years, and that it is becoming gradually more serious year by year. Additionally, 90% of them are concerned about the availability of future repair material. These facts show that the insufficiency of materials will make it difficult to perform the needed cultural asset repairs. To ensure that timber cultural properties are maintained, information must be shared by people who repair cultural properties and those who manage forests, and the necessary systems must be put in place.

The International Council on Monuments and Sites (ICOMOS), which is under the United Nations Educational, Scientific and Cultural Organization (UNESCO), has "Principles for the Preservation of Historic Timber Structures" that require the "same species of wood", "same grading", and "same technology". Therefore maintaining Japan's traditional timber structures requires that we accurately ascertain what type of wood and how much is used. We also need to ascertain the extent of required large, long, and high-quality timbers that are hard to obtain on the market, and how much is available. However, in approaching the problem of securing materials for the repair of cultural property structures, there has so far not been enough exchange of, on one hand, information from cultural asset people on the needed quantity and quality of materials, and on the other hand, information from forestry people on how much timber meeting the requirements for cultural asset materials can be supplied and sustainably produced. For that reason, currently no one can accurately answer questions on how much and what kinds of wood are needed for maintaining cultural buildings.

So, the purpose of this study is to achieve mutual understandings of the situation between cultural asset people and forestry people on preservation for traditional timber-frame buildings.

ESTIMATING THE AMOUNT OF TIMBER USED IN CULTURAL BUILDINGS

Let us begin with trying to estimate how much material is needed annually. According to the timber purchase breakdown in a report on structural cultural asset repairs on national treasures and important cultural properties over the 25 years from 1976 to 2000, the average amount used annually is 517 m^3 (SHIMIZU, 2005). However, because of the large individual differences in structure size, state of damage, and other characteristics of structures to be repaired, some elements of uncertainty remain in applying this figure as is.

For that reason I will try predicting repair material demand from a different perspective. The average amounts of materials used according to building type (Buddhist temples, Shinto shrines, castles, dwellings, and folk housing) were determined from an analysis of repair reports to date (MURATA, 2000). These amounts were then multiplied by the number of structures designated as national treasures and important cultural properties. In this way, the total material amount for timber cultural buildings was estimated to be approximately 300,000 m^3 (Table 1). It is a rough method, but in view of the information available at this time, it is presently the only conceivable method. It is reasonable to assume that the true amount of material will be between 50% and 200% of this figure. In a comparison of material amount per square meter of eaves-to-eaves area, it is 0.7 m^3 for temples, 0.4 m^3 for shrines, and 0.2 m^3 for folk housing, but it will be necessary to get still more data and improve the estimation accuracy of material amount per unit eaves-to-eaves area for each type of building (Table 2).

Next is predicting annual demand. There is great disparity in the time intervals for dismantling and repair, depending on building size and environmental conditions. However, investigating the example of Buddhist temples, which account for most of the material, indicates that even for Horyuji Temple, which has a history of 1,300 years, the structures have so far

Table 1 Total material amounts in cultural buildings

	No. of structures	Average volume (m^3)	Total volume (m^3)
Shrines	1,183	22	26,026
Temples	1,253	187	234,311
Castles	250	40	10,000
Dwellings	168	44	7,392
Folk housing	680	28	19,040
Totals	3,534	84	296,769

Note; Average volume is quotation from MURATA (2000).

Table 2 Amounts of materials and replacement rates per unit eaves-to-eaves area

	Volume (m^3) per eaves-to-eaves area (m^2)			Replacement rate (%)		
	Dressed lumber	Rough lumber	Totals	Dressed lumber	Rough lumber	Overall
Shrine average	0.290	0.103	0.393	52.2	90.8	62.3
Temple average	0.389	0.311	0.700	31.1	52.7	40.7
Folk housing average	0.107	0.060	0.199	55.1	42.0	50.4

Note; plane area for folk housing, quotation from MURATA (2000).

been maintained by major repairs performed at intervals of about 300 years (OSAWA *et al.*, 2005). From the standpoint of sound maintenance of structures, here I will assume the dismantling and repair interval to be 200 years. Judging from the historical data on repairs given above, the average material replacement rate for temples is set at 40%. This figure could swing considerably either way depending on factors such as structure size and state of damage, and for shrines, the average material replacement rate is over 60%. For dressed timber, of which much is large-diameter and long, the figure is about 30%, while for rough lumber, which is often yard lumber, it is over 50%, but the percentage found from currently available data is the above 40%. Lumber 5 m or longer or 36 cm or wider is estimated to be about 40% of that.

Dividing the total material amount of 300,000 m^3 by the repair interval of 200 years and multiplying by the 40% replacement rate yielded an annual amount of 600 m^3. This value almost agreed Shimizu's report. However, because this is the final amount used, one must work backward to find the amount needed in the forest. At the first stage, one must estimate about 30% carpentry waste produced when cutting lumber at the repair site, and therefore lumber delivered to the site will be 1.3 times this amount. At the second stage, the lumber yield when processing lumber is less efficient than for yard lumber, making for an estimated 50%. For that reason, one will need a quantity of logs twice the required amount of finished lumber. These estimates of carpentry waste and lumber yield are based on interviews with sawmillers. At the third stage, one needs to examine the yield between standing timber and logs, which is generally estimated at 70%. Thus, when working backward from the materials used, the volume of standing timber actually needed in the forest was 3.7 times the amount of materials used in buildings. Accordingly, annually a volume of 2,220 m^3 in standing trees was needed to secure 600 m^3 of repair materials. But to provide the wood species and quality of the material actually sought, 2,220 m^3 of wood in the forest will not be enough. Because wood is carefully selected from among diverse trees, far more forest resources are needed. Additionally, as the above figures are for only government-designated structures, we must also consider cultural properties designated by municipalities.

What is more, because the required materials also include large-diameter and long timbers, this is not just a matter of volume. One must also carefully consider restrictive conditions related to diameter and length. In a literature study on the lengths and diameters of 278 members making up 22 cultural buildings dating before the 8th century, YUMOTO (2005) found that the longest is the 32-m central pillar of the 5-story pagoda at Horyuji Temple, and the second is the 16.6-m central pillar of the East Tower at Yakushiji Temple. Nationally, there are 18 members more than 10 m long. For diameter, the largest are the members used in the doors of the main building of Todaiji Temple, some of which are 1.3 m in diameter. There are 5 members exceeding a diameter of 1 m. It is necessary to carry out a broad study of such large timbers, and examine the possibility of procuring the forest resources.

Also to be considered is quality. According to the previously cited repair report, amounts used for replacement are 27 % cypress, 21% cedar, and 19% pine (SHIMIZU, 2005). The top 3 conifer species account for over 2/3 of the materials used in repairs. Other major species are *Thujosis dolabrata* and *Tsuga sieboldii*. Securing large-diameter pine is now difficult because of the damage to pine forests in Japan by the pine wood nematode (*Bursaphelenchus xylophilus*). During the Showa era (1926–1989) Taiwan cypress is used, accounting for some 2 %, but its logging is now banned, and consideration of how to secure large-diameter cypress timbers is needed. With respect to grades of the 3 species most used, the percentages of knotless timbers and those with fine small knots are 27% for cypress, 23% for cedar, and 25% for pine, which are exceedingly high percentages of high-quality materials compared with general building materials (SHIMIZU, 2005).

Since the 1930's, more than 1,600 reports have been prepared on repairs thus far performed, but as there is not necessarily a certain way in which reports must be written, in many instances the total amounts of materials in buildings is not known. The Great South Gate of Todaiji Temple, a national treasure, was repaired in 1930, and its repair report is the

oldest. Because it records the standards and numbers of all materials used, we know that the building uses 1,044 m^3 of materials, that its 18 pillars account for 20%, and that there were 112 m^3 of supplementary materials. The reason for the low replacement rate of 10.7% would seem to be the large proportion of large-diameter members. Owing to the 25.5-m height of this building, its amount of wood used per unit area is twice the average for temples. Toshodaiji Temple's Golden Hall, which is now being dismantled and repaired, uses 621 m^3 of materials. The estimated amounts of wood in the buildings making up Horyuji Temple's Sai-in area are 289 m^3 in the gallery, 251 m^3 in the Golden Hall, and 252 m^3 in the Great Teaching Hall (YAMAMOTO, 2006). Estimated on the basis of the material amounts used per unit eaves-to-eaves area, mentioned above, the average amount of wood used per square meter in timber-framed cultural buildings is on the order of 0.5 m^3. This amounts to 5,000 m^3 per hectare, which means that these structures fix about 10 times the carbon as ordinary forest, for at least several hundred years.

FOREST RESOURCES FOR MAINTAINING TIMBER-FRAME CULTURAL BUILDINGS

I shall now examine whether the supply capacity of Japan's forest resources can satisfy the demand for maintaining cultural buildings. The Forestry Agency's Planning Division (2002) states that cedar accounts for the biggest area of plantation forest in Japan at about 45%, followed by cypress at about 25% and pine at about 9%. Their stocks are 1.34 billion m^3 of cedar, 490 million m^3 of cypress, and 170 million m^3 of pine. But if these are limited to aged trees at least 80 years old, which are in demand for repairing cultural buildings, then cedar plantation stock is 44.79 million m^3, and cypress plantation stock is 19.62 million m^3. Estimated stocks distributed in natural forests are 6.99 million m^3 cedar and 7.92 million m^3 cypress. While there are quantitatively sufficient stocks of cedar and cypress to meet demand, questions about quality need to be answered. Tabulated data on the current state of pine forests show an estimated 190 million m^3 in natural forests, but that amount has plunged in recent years due to severe damage by pine wood nematodes, making recovery of pine resources difficult for the time being. Because there is little damage by this nematode in cold regions, securing pine forests in the northern Tohoku region and high-altitude regions is of vital importance. Demand for *Zelkova serrata* is also expected, but unlike cedar and cypress, there is no viable technique for growing *Zelkova serrata* in plantations. Although there are records of plantations having been created in the past, there are hardly any mature plantations, and it is estimated that there are about 220,000 m^3 of natural trees. Many chestnut trees were planted in orchards, but none have attained large diameters, and natural trees are estimated to amount to about 480,000 m^3. These hardwood trees rarely grow in groups within natural forests, and large-diameter trees are found scattered throughout natural forests. Thus although there is sufficient stock to accommodate demand, but when it comes to actually supplying the trees, there are few sales of large-diameter trees, and a system to accommodate demand is lacking. As such, it seems there is a sense of tight supply.

On the state of cypress resources, for which there is the greatest demand, I noted above that cypress forests account for about 10% of Japan's forest resources in terms of both area and stock. Because most plantations have been planted since 1950, they are still young and cannot soon be used for cultural assets. Mature plantations that can be used for repairs are about 5% of the total; of that 5%, 3/4 are privately owned, and half of those privately owned plantations are concentrated in the prefectures of Gifu, Aichi, Nagano, Nara, and Kyoto. Natural trees, on the other hand, are distributed from Yakushima Island to Fukushima Prefecture. Distribution is concentrated mostly from Hakone westwards, in Nagano and Gifu prefectures, and from Kiso to Tono. Most is in the national forests stretching from Kiso to Tono.

The amount of cypress logged in Kisodani was verified on the basis of the Report on the Regional Cultural Asset Forest Initiative (JAPANESE ASSOCIATION FOR PROTECTION OF ARCHITECTURAL MONUMENTS, 2003). Although there are records of logging from the 14th century for shrine rebuilding and other reasons, heavy use is said to have started in the 16th century when cypress resources in Western Japan underwent a pronounced decline (Fig. 1). In the 17th century there was increased logging for temple construction and castle-building materials by the Owari Clan. There was a time when 300,000 m^3 was logged annually, and it is thought that logging in this period engendered the natural regeneration that produced the current natural trees. But concerns about resource depletion in the 18th century led to subsequent strict protection policies, which meant less natural regeneration. Nevertheless, logging of between 50,000 and 80,000 m^3 annually continued. With the Meiji Restoration, the cypress forests came under the new

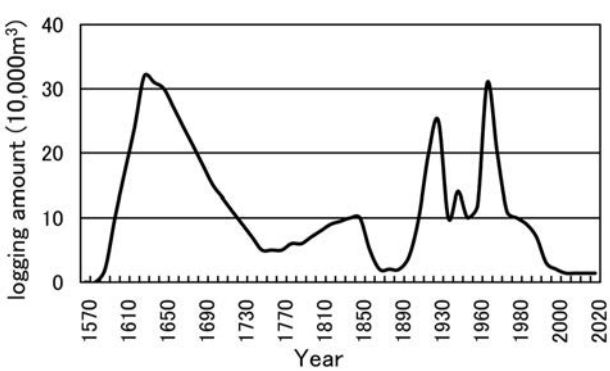

Fig. 1 Logging amount of Kiso cypress
prepared using Chubu Regional Forest Office data; quotation from JAPANESE ASSOCIATION FOR CONSERVATION OF ARCHITECTURAL MONUMENTS (2003).

government's jurisdiction, and for the establishment of imperial family assets, the forests were managed as an imperial estate from 1889 to 1947. During the Meiji period, logging was kept at a low level, but in 1916 forest railways were laid, and logging increased in the 1920s to about 200,000 m^3 a year. At that time, the approach to forest management changed from the selective cutting practiced theretofore to clear cutting and blanket afforestation. However, around 1930, the approach to the management of imperial forests changed from expansive afforestation to selective cutting, and the amount of Kiso cypress supplied averaged 100,000 m^3 yearly. In 1947, the forest was changed from an imperial family asset to a national forest. Beginning about 1960, Japan as a whole experienced a timber shortage. Forest policy changed, expansive afforestation was promoted, and logging increased. The logging of trees severely damaged by the Ise Bay typhoon resulted in increased logging, and brought the amount to 310,000 m^3 in 1964. In 1973, logging policy for national forests again changed to selective cutting, and from 1975 the amount fell to 100,000 m^3, and in FY2001 it was 20,000 m^3. Under the Chubu Regional Forest Office's plan, with current stock of 3.7 million m^3 as the resource base, it is possible for the time being to stably provide timber at an annual average level of 14,000 m^3 .

But while this plan responds to demand quantitatively, one must examine it to see whether it can sustain a qualitatively high level. According to 2001 data from the Chubu Regional Forest Office, half of the 20,000 m^3 sold was knotty, and about 22% of the timber with small-end diameters of at least 40 cm was of good quality with few knots. What is more, good-quality, long timbers of 7 m or more in length accounted for about 3%. With these facts in mind, it will be necessary to consider, from the standpoint of quality, what level of quality to seek. It will be necessary to ascertain the demand for each tree species to find the quantities of long and large-diameter timbers needed.

SECURING SHRINE REBUILDING MATERIALS

The rebuilding of Ise Shrine started in 690 and the 62nd rebuilding is scheduled for 2013. A characteristic of shrine rebuilding is that the amount of needed wood and the time period are known in advance, allowing preparations to be made in a planned manner. On the occasion of the 58th rebuilding, the Ise Shrine Rebuilding Agency issued a breakdown of the 11,705 logs ordered from the Imperial Household Forestry Bureau by length and small-end diameter (KURATA, 1939). The volume of these logs exceeded 10,000 m^3. The largest small-end diameter was 122 cm with a length of 4 m, the longest log was 13 m with a small-end diameter of 40 cm, and 25% of the needed logs, or 3,000 logs, were at least 6 m long or had small-end diameters of at least 30 cm. Of these, the large logs at least 6 m long and with small-end diameters of at least 50 cm accounted for 42% of the whole by volume. Combining these data with a cypress log taper table enables one to find the number of trees needed by tree diameter at breast height (DBH). If all first-cut wood is used, then standing tree volume will be 4.5 times that of log volume, or 45,000 m^3. When these are plotted by diameter, the result is Figure 2. The most numerous are logs with a DBH of 52 cm, but there were 613 logs measuring 70 cm or more.

Around 1930, an imperial forest technician used such data to calculate the area of shrine forest needed to secure wood for shrine rebuilding. Yoshio KURATA (1939), a technician at the Imperial Household Forestry Bureau, investigated the growth of natural trees and the percentage of dead standing trees on site, and calculated that 185,000 trees are needed to supply shrine reconstruction timber every 20 years. Further, assuming a suitable tree rate of 40% and a 2.5-fold safety factor, he calculated that 1,000 ha is needed to raise 461,000 trees, and then supplementing the trees cut for interim thinning, that 1,719 ha of pure natural forest is needed. Further assumptions he made included a 50% mixture of other tree species, and that 20% of the land would be unsuitable for producing large-diameter trees, and concluded that in total over 4,400 ha would be needed for shrine rebuilding forest (KURATA, 1939). But a 1934 management proposal set the shrine rebuilding forest at 8,228 ha comprising a total of 12 locations with permanent forest of 4,484 ha, temporary forest of 1,778 ha, and supplementary supply forest of 1,996 ha. This shrine forest system was established in 1904 to sustainably supply the timber needed for the periodic rebuilding of Ise Shrine. Under provisions of the day, cutting large cypress trees in the forests for a purpose other than shrine building was prohibited, and tree species other than cypress were cut to facilitate the natural regeneration of cypress. According to records, forest logging actually occurred around 1921 when 17,000 trees were cut for the 1929 reconstruction, and there was logging during the war for use in the 1949 reconstruction.

Since the transfer of the forests to the Forestry Agency after the war, it is no longer possible to manage them for Ise Shrine, but these forests now total 13,924 ha by combining a variety of management groups such as the "Kiso Cypress

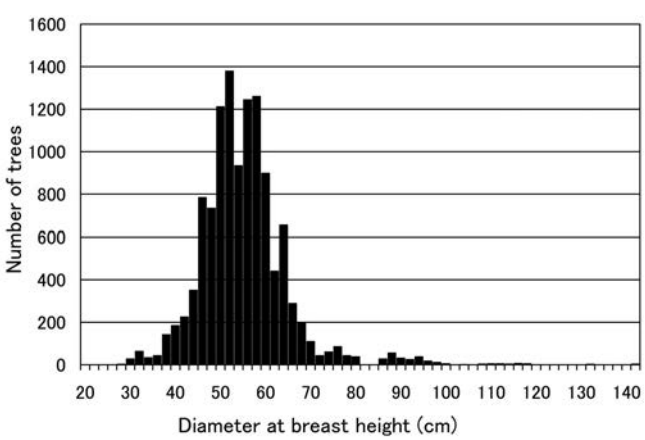

Fig. 2 Numbers of cypress trees by diameter needed to rebuild Ise Shrine

Selective-Cutting Multi-Storied Task Group for Cultural Assets and Other Purposes" and the "Kiso Cypress Large-Diameter Tree Selective-Cutting Production Group for Cultural Assets and Other Purposes." The management program aims for sustainable timber production with a rotation cycle of 200 or 250 years.

It will take some time before we know if the expected natural regeneration goes well, but in general letting forests regenerate themselves will not go well unless about the same amount of time and effort is spent closely observing the forests as is used in clear cutting and blanket afforestation, and considerable energy is used (YAMAMOTO, 2005).

DISCUSSION AND CONCLUSIONS

If one knows in advance the amount of material needed and when, as with the Ise Shrine, it is possible to prepare the forests. However, for many cultural assets it is unknown when they will be repaired and, until actually dismantling them, it is not know how much material will be replaced, the wood species required, or the amounts and standards of each. The reality is that in these ways, the great element of uncertainty is a limiting factor that hinders the formation of a stable supply system. There may be instances in which materials are not used even if secured. If trees are cut after timber is ordered, sufficient dried timber cannot be provided. Therefore, lumber mills and distributors currently take on risk by stocking materials in advance. Doing do involves the risks of price fluctuations and timber deterioration, and it is also possible that when actually milling the timber it will not yield products of the expected quality. The challenge is to build a system which disperses these risks and links suppliers with consumers.

For the time being, to gain the cooperation of forest owners it will be necessary to create silviculture techniques for long-term rotation management of plantation forests, and set up a system to make effective use of the forest thinning of various standards generated in that process. From a long-term perspective, it will also be necessary to work on natural regeneration techniques for producing high-quality materials from natural forests.

So far I have discussed repair materials in terms of supply and demand, and while there is still room for consideration on the demand side about what extent of quality to seek, the prospects are good that many kinds of materials can be supplied in the desired quantities. It seems likely that stable supplies of materials can be secured by creating a system for their actual distribution. To begin with, we must define the scope of cultural assets for which materials must be obtained. There are (1) buildings that are designated and registered under the Cultural Properties Protection Act, mainly national treasures and important cultural properties, and (2) the cultural properties that are local temples and shrines maintained by communities, and the community activities that have sustained those temples and shrines. This discussion is limited to the first. And with respect to the kinds of materials, we need to include not only special wood such as large-diameter, long timbers, but also other plant-based materials such as cypress bark and lacquer.

From the supply side, the character of forests intended to secure repair materials for national treasures, important cultural assets, and the like would be tree ages of at least 200 years, with priority tree species being cypress and pine, while *Zelkova serrata* and cedar must also be considered. At the very least the DBH must be 50 cm, and annual ring width must be under 2 mm. Fulfilling this ring width requirement is difficult with plantations instead of natural forests. But even if that is difficult near the center of a forest, it is possible on the periphery if tree density is properly managed. Yet, that is a tough objective for producers. Further, they must grow forests with many trees that have high lowest branch heights, few knots, and are straight. The ideal has been to use natural timber for replacement materials, but there are as yet no techniques to control natural forests as desired. Producers have not intentionally improved natural forests to meet these requirements, but rather have extracted appropriate materials from trees that just happened to be growing in natural forests. By maintaining natural forests it is possible that high-quality natural trees will grow, but it is not something that can be done on a planned basis. Therefore, from a long-term standpoint the use of plantation timber must be considered. That necessitates the preparation of long-rotation multi-storied forests with dense planting and frequent thinning. Regeneration by natural seeding must also be considered. Although the technical details will need further discussion, this will be the direction to take. And even if it is possible to raise high-quality trees in this manner, it will be necessary to also consider a social system that will put to good use the wood other than that used for cultural asset repairs, such as the semi-high-quality wood, general-use wood, culled trees, and other timber produced in the process of raising these forests.

When repairing cultural buildings, the amount of replacement materials needed is only known once a structure is dismantled. If something is not replaced in the present rebuilding, those materials are not used until the next repair 200 years in the future, and storing the materials until then presents difficulties. As such, preparing certain trees for those materials involves too many elements of uncertainty. For that reason, unless one assumes the probability of material replacement in advance and predicts the amount needed for a number of cultural buildings as a whole, a large amount of waste will arise on the supply side, which creates the problem of who will assume the burden.

Until now, much of that burden has been assumed by saw millers, distributors, and forest owners, and that has made these materials far more expensive than general-use timber. For society as a whole to support the maintenance of cultural assets, it will be necessary to disperse these risks as much as possible and take creative measures to hold down material

procurement costs. Additionally, technical support measures are needed for forest owners to grow high-quality, large-diameter trees, and measures are needed to effectively use and raise the market value of timber that is produced but is not suitable for cultural asset repairs. That in turn makes it necessary to increase the building of large-dimensional timber structures using large-diameter timbers, thereby inducing change in the manner of timber construction so that large-diameter timbers are primary. This will make it possible to log plantation trees at larger diameters and provide for longer rotation cycles.

One area of future research is to develop a technique to predict with some degree of accuracy the replacement materials required for a building to be repaired, before it is dismantled for repair.

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Article

How Forest Management and Climate Change Affect the Carbon Sequestration of a Norway Spruce Stand?

Raisa Mäkipää[*1], Tapio Linkosalo[*1], Sami Niinimäki[*1,3], Alexander Komarov[*2], Sergey Bykhovets[*2], Olli Tahvonen[*1,3] and Annikki Mäkelä[*3]

ABSTRACT

Mitigation of climate change by forest carbon sequestration is one of the ecosystem services that will be taken into account in future forest planning. The potential capacity of forests to sequester carbon is determined by edaphic and climatic factors, but the actual carbon accumulation is highly controlled by management. The effects of the management practices on stand development are successfully analyzed with traditional stand simulators that rely on empirical data. One of the current challenges is to understand how ecosystem services, such as carbon sequestration and timber production, can be managed in the changing climate, i.e. under conditions of which there are no observations. The objective of this study was to investigate the responses of forest soil and vegetation to a climate change under different management scenarios ranging from intensive thinning to unmanaged stands. The responses of tree growth and forest carbon sequestration to changes in temperature and precipitation (+3 ℃ and +10%, respectively) under different management scenarios were investigated with a process-based forest model (PipeQual) which was combined to a soil decomposition model (ROMUL) and a soil water balance model. According to our simulations, the growth response of Norway spruce to increased temperature was positive. Carbon stocks of both vegetation and soil were increased with the changing climate in all the simulated management scenarios. In the changing climate decomposition of soil organic matter was accelerated, however, increased litter input resulting from enhanced growth of vegetation compensated this decrease. Intensively harvested stands had a decreased carbon stock in the vegetation, which resulted in low litter production and decline in soil carbon stock after thinnings. The simulations with the process-based forest growth and soil model can guide management by determining a sustainable level of biomass harvest.

Keywords: carbon sequestration, climate change, forest management, growth modeling, soil decomposition model

INTRODUCTION

Forest carbon sinks have a significant role in global carbon balance, and the mitigation of climate change by forest carbon sequestration is one of the ecosystem services that will be taken into account in future forest planning. Forest carbon sinks and sources resulting from forest management and land-use changes were already included in the Kyoto protocol (UNFCCC, 1997) and, most likely, forests are increasingly considered in the future commitments under the Climate Convention. Thus, evaluation of the management systems in terms of their influence on carbon balance is needed for future planning of effective measures to mitigate climate change. The effects of climate change on coniferous forest ecosystems have been widely studied by model simulations (e.g. Ge *et al.*, 2010; Kellomäki and Kolström, 1993; Kellomäki and Kolström, 1994; Kellomäki *et al.*, 2008; Lasch *et al.*, 2005; Mäkipää *et al.*, 1999;

Corresponding author: Raisa Mäkipää
E-mail: raisa.makipaa@metla.fi
[*1] Finnish Forest Research Institute, P.O.Box 18, FI-01301 Vantaa, Finland
[*2] Russian Academy of Sciences, Institute of Physicochemical and Biological Problems in Soil Science, Institutskaya ulitsa 2, Pushchino, Moscow Region, 142290 Russia
[*3] University of Helsinki, P.O. Box 27, FI-00014 University of Helsinki, Finland

WANG *et al.*, 1996). The potential of forest management practices to influence the forest-atmosphere carbon balance in the changing climate can also be analyzed with process-based models (see however BRICEÑO-ELIZONDO *et al.*, 2006; LASCH *et al.*, 2005; MIKHAILOV *et al.*, 2004). Such analysis, including extreme management options ranging from non-managed forests to intensive harvests, could guide the forest policy that is aiming to mitigate climate change with modified management practices.

At a landscape scale, variation in the forest carbon sequestration results from age-class distribution and the amount of harvests, as well as from year-to-year variation of the climatic parameters (LISKI *et al.*, 2006). At a stand scale, the potential capacity of forests to sequester carbon is determined by edaphic and climatic factors, but the actual carbon accumulation is highly controlled by management, i.e., the timing and intensity of the harvests (thinning and final cutting) and the proportion of the removed biomass (LASCH *et al.*, 2005; MÄKIPÄÄ *et al.*, 1999; NABUURS *et al.*, 2008; PALOSUO *et al.*, 2008; PUSSINEN *et al.*, 2002). The effects of management on forest carbon stocks are typically evaluated with stand simulators that rely on empirical data (e.g. HYNYNEN *et al.*, 2005; PALOSUO *et al.*, 2008), but their applicability to new stand structures and changing climatic conditions cannot be validated. One of the current challenges is to understand how ecosystem services (e.g. carbon sequestration, timber production, ecosystem functions maintained by diversity of species) can be managed in the changing environment, i.e., under conditions of which there are no observations.

Changes in the climate will affect both the primary production and the decomposition of organic matter. Understanding tree growth and its interaction with soil processes is required for projections of forest carbon sequestration potential in different management and climate change scenarios. Both at large scale and at a stand scale, the carbon stocks of vegetation and soil may change in either direction, which underlines the importance of including all relevant carbon pools into the analysis (LISKI *et al.*, 2006; MÄKIPÄÄ *et al.*, 1999). KARJALAINEN *et al.* (2003) predicted that, under changing climatic conditions, the carbon sinks of both trees and soil will be larger than under the current climatic conditions. In Finland, average growth was predicted to increase by 30% resulting in a 30% increase in biomass C stock and a 7% increase in soil C stock (KELLOMÄKI *et al.*, 2008). In southern Finland, the growth response of Norway spruce to climate change was predicted to be marginal or even negative (KELLOMÄKI *et al.*, 2008). On the other hand, JANSSON *et al.* (2008) predicted that light use efficiency and water use efficiency will be improved in the future climate, resulting in increased productivity of Norway spruce stands. Based on simulations of various management alternatives with a process-based model, LASCH *et al.* (2005) concluded that the average values of carbon stocks showed hardly any net effect of climate change in the temperate mixed pine-broadleaved forests. Thus, the overall sensitivity of carbon sequestration of the boreal spruce stands to climate change remains unknown.

Several studies have indicated a considerable potential for carbon sequestration with alternative management practices (e.g. KELLOMÄKI *et al.*, 2008; e.g. LASCH *et al.*, 2005; PUSSINEN *et al.*, 2002). In general, long rotations and low intensity of thinnings have been shown to be favorable for forest carbon sequestration (LASCH *et al.*, 2005; LISKI *et al.*, 2001; PUSSINEN *et al.*, 2002). Furthermore, climate change has been predicted to enhance carbon sequestration in managed forests (e.g. HYVÖNEN *et al.*, 2007; KELLOMÄKI *et al.*, 2008). Currently, carbon sequestration is not a major objective of forest management. Rather, forests are managed for sustainable timber yield and economical profitability. The influence of more intensive harvests proposed by economical optimization of forest management (HYYTIÄINEN *et al.*, 2004) on forest carbon balance has not been analyzed.

With a process-based growth model (KANTOLA *et al.*, 2007; MÄKELÄ and MÄKINEN, 2003) combined to a similar model of decomposition of soil organic matter and a soil water model (CHERTOV *et al.*, 2001), the responses of photosynthesis and respiration as well as the allocation of photosynthetates and dynamics of organic matter in the soil can be analyzed. We believe that analysis on growth response of Norway spruce with a process-based model will yield improved understanding of the effects of management practices on forest growth and carbon sequestration in the changing conditions. Coupling of the dynamic stand and the soil models makes it easy to determine the whole dynamics of carbon within the forest ecosystem, including both the stand and C sequestration into the soil. With the designed set of growth and soil models, one can analyze differences of the proposed management scenarios in terms of timber production and carbon stock changes of forest vegetation and soil. The relative sensitivity of carbon sequestration in the different management scenarios to the changing climate will be assessed in order to understand the potential risks and sensitivity of forest carbon to management and climatic conditions.

The objective of this study was to investigate the responses of tree growth and forest carbon sequestration in Norway spruce stands to changes in temperature and precipitation under different management scenarios. The management scenarios were: (i) thinnings from below and final harvest according to the current recommendations, (ii) a management plan based on economic optimization (delayed thinnings from above with higher removals and early harvest), (iii) natural development without management.

METHODS

Modelling

The model troika used in this study consists of three process-based models: the PipeQual stand growth model (KANTOLA *et al.*, 2007; MÄKELÄ and MÄKINEN, 2003; MÄKELÄ *et al.*, 2008), the Romul decomposition model for litter and soil

organic matter (CHERTOV *et al.*, 2001) and a simple model for the soil water content and temperature (Fig 1). The stand growth model simulates the development of the stand depending on environmental conditions and management and produces, among other things, output of the produced litter, which is then used as an input for the decomposition model. The soil climate model uses daily weather data (air temperature, irradiance, water vapor pressure deficit and precipitation) to simulate soil conditions which are then used as an input for the decomposition model. The decomposition model simulates the dynamics of the organic matter in the forest floor and soil.

The process-based growth model PipeQual (KANTOLA *et al.*, 2007; MÄKELÄ, 1997; MÄKELÄ and MÄKINEN, 2003) was used as the stand growth simulator (Fig. 2). The model represents trees in terms of biomass and form in a hierarchical structure comprising tree, whorl, and branch levels. At the tree level, the biomass components include foliage, fine roots, stem, branches, and transport roots biomass, and the tree form is described by tree height, diameter, crown ratio, crown width, and root system extension. At the whorl level, the whorl module describes the vertical structure of stem and branches. At the branch level, the branch module provides the annual dynamics of individual branches and their properties in each whorl. The stand consists of several tree size classes each represented by a mean tree of the size class, and the distribution of trees is assumed random.

Tree growth is calculated on the basis of photosynthesis and the growth and the maintenance respiration of live biomass components. Tree photosynthesis is based on the canopy GPP and its allocation between trees on the basis of their size and position with respect to shading. Total growth is allocated to the biomass components on the basis of structural constraints, including the pipe model (SHINOZAKI *et al.*, 1964) and the theory of crown allometry (MÄKELÄ and SIEVÄNEN, 1992). These also determine the extension growth of the dimensional variables. Mortality is calculated using a semi-empirical model and is mainly related to competition for light.

The impacts of weather have been included in the present (preliminary) model version through effective temperature sum (ETS), which in Finland has been found to be a good proxy for the climate-related variation of GPP (HÄRKÖNEN *et al.*, 2010). The effective temperature sum (ETS) was defined as the sum of those daily mean temperatures that exceeded the threshold temperature (+5 ℃). ETS has an impact on the stand level GPP (HÄRKÖNEN *et al.*, 2010), the specific maintenance respiration rates, and the allocation of growth between foliage and wood (PALMROTH *et al.*, 1999).

The Romul decomposition model was presented by CHERTOV *et al.* (2001), and is a further development of the earlier SOMM model (CHERTOV and KOMAROV, 1996; CHERTOV and KOMAROV, 1997). Our application utilizes a new set of functions defining the decomposition rates of soil ash and nitrogen content, temperature, and soil water (CHERTOV *et al.*, 2007) (Appendix 1). The Romul model handles the litter as separate cohorts based on the origin (litter from needles, shoots, fine roots, coarse roots and stems), which makes coupling with a stand model most straightforward. The model has two parallel mass flows, one for the soil organic matter (SOM) and the other for the corresponding nitrogen. These are presented as separate mass flows, but the nitrogen content of the organic matter in the decomposing soil affects the decomposition rate in many phases (Fig. 3).

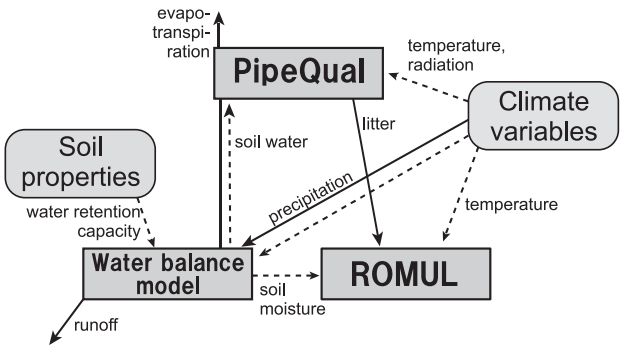


Fig. 1 The applied process-based forest model (PipeQual) was combined with a soil water balance model and a soil decomposition model (ROMUL)
Solid lines, flow of material (litter or water); dotted lines, influence.

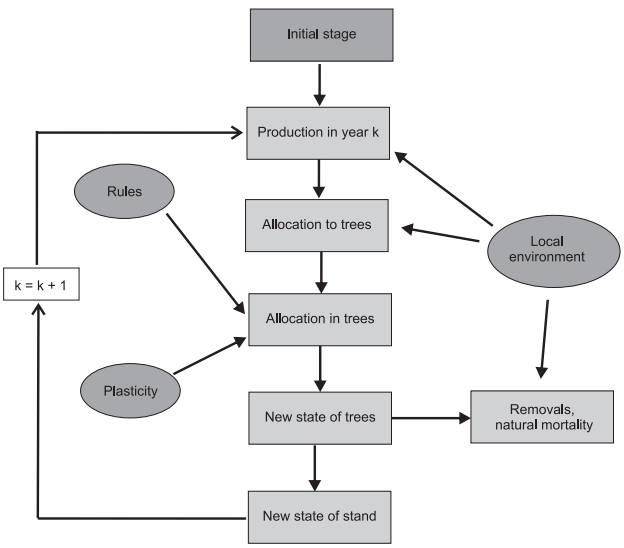
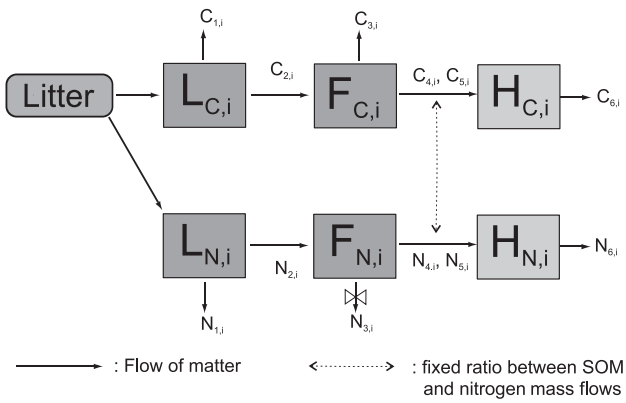


Fig. 2 The structure of the stand growth model (PipeQual)

The fresh litter enters the model in storages for undecomposed litter ("$L_{C,i}$" for SOM and ("$L_{N,i}$" for corresponding N, in Fig. 3), where "i" refers to the separate cohorts for litter from different origins. Part of this litter is metabolized by the decomposing organisms, and the corresponding carbon is released as gaseous CO_2 (flows $C_{L,i}$ in Fig. 3). Majority of the organic matter ends up in a more slowly decomposing complex of



index i refers to *needle*, *shoot*, *fine root*, *coarse root* or *stem*

SOM / carbon fluxes

$C_{1,i} = k_{1,i}(L_{N,i}/L_{C,i}$, L_i ash content, soil T, soil REW) · $L_{C,i}$

$C_{2,i} = k_{2,i}(L_{N,i}/L_{C,i}$, L_i ash content, soil T, soil REW) · $L_{C,i}$

$C_{3,i} = k_{3,i}(F_{N,i}/F_{C,i}$, L_i ash content, soil T, soil REW) · $F_{C,i}$

$C_{4,i}$, $C_{5,i}$ depend on corresponding nitrogen fluxes $N_{4,i}$, $N_{5,i}$, with a spesific C/N -ratio of 24.0 for *Bacteria* and *Aithropoda*, and 12.8 for *Lumbricidae*

$C_6 = k_6(H_N/H_C$, H ash content, soil T, soil REW) · H_C

Nitrogen fluxes

$N_{1,i} = k_{1,i}(L_{N,i}/L_{C,i}$, L_i ash content, soil T, soil REW) · $L_{N,i}$

$N_{2,i} = k_{2,i}(L_{N,i}/L_{C,i}$, L_i ash content, soil T, soil REW) · $L_{N,i}$

$N_{3,i} = k_{3,i}(F_{N,i}/F_{C,i}$, F_i ash content, soil T, soil REW) · $F_{N,i}$

$N_{4,i} = k_{4,i}(F_{N,i}/F_{C,i}$, F_i ash content, soil T, soil REW) · $F_{N,i}$

$N_{5,i} = k_{5,i}(F_{N,i}/F_{C,i}$, F_i ash content, soil T, soil REW) · $F_{N,i}$

$N_6 = k_6(H_N/H_C$, H ash content, soil T, soil REW) · H_N

Fig. 3 A flow-chart and mass-flow functions of the ROMUL model

partly decomposed organic matter and humus (flows C_{2i} and storages "$F_{C,i}$" in Fig. 3). Some of the material in the "$F_{C,i}$" storages is also metabolized by the decomposing organisms, releasing a further amount of gaseous CO_2 (flows C_{3i} in Fig. 3).

Parallel to the flux of soil organic matter, nitrogen in the litter is stored in the storage L_{Ni}, and it flows, as a result of decomposition, into the storage F_{Ni}. The nitrogen flux out of the system (N_{1i} and N_{3i}), corresponding to the release as gaseous CO_2 from the decomposition of SOM, is considered mineralized nitrogen, thus in a form available to plants.

The contents of the storages $F_{C,i}$ eventually ends up in the storage of immobilized humus ("H_C" in Fig. 3). There is only one common storage "H_C" for immobilized humus, unlike the previous phases, where the organic matter was divided into cohorts based on the litter origins. The first three decomposition coefficients (k_1, k_2, k_3) are obtained by statistical methods from laboratory experiments with different litter cohorts. The coefficients of decomposition, $k_{i,j}$, (j=1..3) depend on the nitrogen and ash content of the originating cohort, as well as the soil temperature and water content. The k_6 coefficient for soil decomposition is constant, hence the decomposition of H fraction is modified only by temperature and soil moisture. The corresponding coefficient for nitrogen mineralization from the H fraction has an additional component slowing down the process when C/N ratio in the humus compartment is low (Chertov *et al.*, 2001).

The transformation of organic matter into the compartment H_C, i.e. mass flows $C_{4,1}$ and $C_{5,1}$, is based on the assumption that all the matter in the compartment "H" is mostly produced by the metabolism of the decomposing organisms (*Bacteria*, *Arthtropoda* and *Lumbricidae*), and we use a C/N ratio for these groups obtained from soil biology experiments. Therefore, nitrogen has a special role in this phase: first, the rate of nitrogen moving from compartments $F_{N,i}$ into the compartment H_N is calculated using some modifiers in the main scheme of SOM decomposition, because carbon and nitrogen dynamics have different rates of transformation, and thereafter, a corresponding amount of organic matter, typical for the type of decomposers and depending on the C/N ratio of produced humus (24.0 for *Bacteria* and *Arthtropoda* and 12.8 for *Lumbricidae*), is moved from the compartments $F_{C,i}$ to the compartment H_C.

The immobilized humus pool is also decomposing, at a rather slow rate, modified by the soil temperature and moisture conditions. The decomposition flux, C, has a range of a minimum 1–2% annually up to 15% annually, depending on the soil texture and the clay content. Maximal rate of H decomposition may be observed for arable soils. On the other hand, as roughly half of the soil organic matter in the boreal zone is in the compartment H, the value of the rate factor k_6 has a significant effect on the total storage of organic matter in the soil.

The temperature and soil moisture modifiers of the fluxes take a variety of forms, given as step-vise defined functions. Typically, all these show an optimal range of values, where the decomposition takes place at a full rate and tapers off outside the optimal conditions (Appendix 1). The optimal conditions for different fluxes are, however, somewhat different.

The soil water model is a simple application of an "open bucket" type model. In other words, it considers the soil a vessel, or a bucket, holding the water within. The bucket is filled with precipitation. The "depth" of the bucket translates into the soil water holding capacity, or the difference between saturation, at which the soil can no more hold the water, and a wilting point, at which plants cannot extract any more water remaining in the pores of the soil. Once the saturation point is exceeded, any additional water flows out of the system. Evapotranspiration (ET) drains the bucket. ET depends on stand characteristics, but most of all, environmental conditions. Here we used a simple relationship obtained as a statistical fit to evapotranspiration data from eddy covariance measurements in Hyytiälä, Southern Finland (Ilvesniemi *et al.*, 2010). Although the model is preliminary, there is already an indication that it does work for a wide variety of vegetation types and

weather conditions, even with the same parameterization (unpublished work). Therefore, the ET model was used independently of the stand model.

The ET model is as follows:

$$E_t = [E_0 \cdot f(PAR) \cdot f(T) \cdot f(VPD) + a_1 \cdot PAR + a_2] \cdot f(\theta), \quad (1)$$

where E_0 is maximum rate of evapotranspiration, $1.74 \cdot 10^{-2}$ (mm/day), constants a_1 = 0.0007 and a_2 = 0.0836, $f(PAR)$ is a modifier function depending on PAR, $f(T)$ is a modifier function depending on delayed temperature average with a time constant of 14 days, and $f(VPD)$ is a modifier function depending on the water vapour pressure deficit VPD.
Function $f(\theta)$ is a drought modifier (DUURSMA *et al.*, 2008) based on the relative soil water content θ:

$$f(\theta) = \begin{cases} 0, & \theta \leq 0.1 \\ \dfrac{\theta - 0.1}{0.05}, & 0.1 < \theta < 0.15 \\ 1, & \theta \geq 0.15 \end{cases} \quad (2)$$

The soil temperature model is a simple delayed average driven by the air temperature, with a low limiter:

$$\Delta T_{Soil} = (T^*_{Air} - T_{Soil}) / \tau, \quad (3)$$

and

$$T^*_{Air} = \max(T_{Air}, T_{\min}). \quad (4)$$

where $T_{\min}$ = −0.45℃ = minimum soil temperature, T_{Soil} = actual soil temperature, T_{Air} = air temperature, and τ = time constant (8.3 days).

We represented the current climate using a mean of daily temperature and the precipitation data from the period 1961-2007, supplied by the Finnish Meteorological Institute (Appendix 1). For PipeQual simulations, this was further used for computing the respective ETS. The geographic location for the calculations was Southern Finland.

A simple method of uniform temperature and precipitation increases were used to simulate the climate change. The current predictions for the A2 climate change scenario (IPCC, 2001) suggest an increase of about 10% in precipitation and +3 ℃ of the average temperature in the summer months for Southern Finland, which is why the changed climate conditions were simply to simulated by adding 3℃ for each temperature value in the "average year" data and the corresponding rainfall figures were multiplied by a value of 1.1. The addition of 3 Celsius degrees underestimates the warming of the winter months somewhat, but this is not considered to have much of an effect on the decomposition in the soil.

For the PipeQual model, it was estimated that the temperature sum of 1,720 degree days corresponds to a temperature rise of 3 degrees, compared to the calculated temperature sum of 1,200 degree days for current conditions. These values were used as the simulation inputs for the model.

Management Options

All the simulations were started as if the stand had been previously managed according the current recommendations and had been growing in the current climatic conditions. In other words, the initial state of soil carbon and nitrogen stocks, similar for all simulations, was derived from the end state of such a simulation. The initial litter input to the system was the final state of such a simulated stand, short of the stem wood, therefore simulating a harvest where the entire harvest residue was left to decompose in the stand.

We simulated the stand development and soil conditions under 3 management options (Table 1). The first option is based on the recommendations of the national authority for good practice guidance and the recommendations for forest management (Tapio Forest Center). This conventional scenario has the primary aim of timber production. According to this option, the stand is thinned twice, based on reaching a target basal area which also depends on the dominant height. The thinnings are from below, leaving the dominant trees to grow until final harvest.

The second option aims in optimizing the monetary outcome from the stand. This economical optimum has been calculated with a model that incorporates PipeQual, economics and optimization (HYYTIÄINEN *et al.*, 2004). The parameters are fixed throughout the optimization period, for example prices are constant and the interest rate is 3%. In the applied version of the model (NIINIMÄKI *et al.*, manuscript), the roadside prices we choose (51.17 € per m^3 for sawtimber and 25.00 € per m^3 for pulpwood) were in line with 2009 levels and reflect the fact that Finnish forest sector is in transition and that timber demand and prices are predicted to be at somewhat lower levels compared to their history (HETEMÄKI and HÄNNINEN, 2009; HÄNNINEN and SEVOLA, 2009). The harvesting costs are calculated using cost models for mechanized cutting and hauling similar to KUITTO *et al.* (1994). The optimization problem uses the classical formula by FAUSTMANN (1849) as the objective function. It calculates the net present value of the stand over an infinite horizon also known as the bare land value (BLV). The optimization was conducted using the generalized pattern search (GPS) algorithm. The optimized variables include, the initial stand density, the number, type and intensity of thinnings, and the rotation period. The maximization of bare land value leads to a rather different management scheme, i.e., the first thinning is delayed compared to the previous conventional management scheme, but the thinning is then more intense, as is the second thinning, and also the overall rotation time is shorter. The use of interest rate shortens the economically optimal rotation period (HYYTIÄINEN *et al.*, 2004; NIINIMÄKI *et al.*, manuscript). The actual structure of the scheme depends, of course, quite heavily on economical parameters, such as the overall interest rate (3%), and the relative prices of pulp and saw timber (HYYTIÄINEN *et al.*, 2004; NIINIMÄKI *et al.*, manuscript).

The third option was a "no-management" one. In other

words, the stand was left to grow without any operations. The reduction of the number of stems is solely due to natural mortality.

RESULTS

Stand Succession and Carbon Stock Changes

The simulated stands were a carbon source for the first two decades after a stand replacing harvest (clear-cutting) in all different scenarios (Fig. 4). The vegetation was remarkable carbon sink for the most of the years after stand establishment (Fig. 5A-5C). The carbon sink of vegetation was highest in the middle-aged stands, but the size of the vegetation carbon sink strongly depended on timing of the thinnings (Fig. 5A, Table 1). At the time of the thinnings, carbon stock of trees decreased remarkably (drop to negative values not shown in Fig. 5A and 5B, but change reported in Table 1). The carbon sink of vegetation was larger for a few years after thinnings in comparision to years before a treatment (Fig. 5A and 5B), but the total carbon sink of vegetation and soil was decreased because soil was carbon source after thinnings (Fig. 6A-6B and Fig. 7A-7B). The carbon removals from a stand at the time of the first and second thinning was 8 Mg/ha and 15.7 Mg/ha, respectively, when the current management regime was applied (Fig. 4A, Table 1).

At the start of the simulation, after a clear-cutting, carbon stock of litter and soil increased as the harvest residues were left on the site (Fig. 4). Thereafter, the soil carbon stock decreased for some 20 years, because the tree biomass was low and consecutively litter fall from the living trees was lower than the amount of carbon released due to decomposition (Fig. 4). After being a carbon source during early succession, the soil tended to turn into a carbon sink; however, the increased amounts of litter following the thinnings increased the decomposition rate and tended to turn the soil into a carbon source, at least for a few years after the treatment (Fig. 6A-6B).

The Effect of Climate Change on Carbon Sequestration of Forest Vegetation and Soil

In the changing climate, both biomass and soil carbon stocks were higher than in the current climate (Fig. 4). In the unmanaged stands of intermediate age, the average carbon sink of vegetation varied from 1.5 to 2.5 Mg/ha/year, being about 1 Mg/ha/year higher in the changed climate (Fig. 5C). When the stands grew older, the difference between the climate options reduced, but finally at the age of 100 years vegetation carbon sink in the changed climate was strongly reduced due to high natural mortality.

In the changing climate, the rate of decomposition increased with temperature and precipitation, but the increase in the biomass stock and litter production was even larger. Thus, in the changing climate the rate of soil carbon sequestration and

Table 1 Harvests in different scenarios under current and changing (A2) climate

Management scenario	Climate	1st thinning				2md thinning				3rd thinning				Final harvest			
		Year	Harvested stem volume	Carbon in harvested stemwood	Carbon in the other harvested biomass compartments	Year	Harvested stem volume	Carbon in harvested stemwood	Carbon in the other harvested biomass compartments	Year	Harvested stem volume	Carbon in harvested stemwood	Carbon in the other harvested biomass compartments	Year	Harvested stem volume	Carbon in harvested stemwood	Carbon in the other harvested biomass compartments
		a	m^3/ha	Mg/ha	Mg/ha	a	m^3/ha	Mg/ha	Mg/ha	a	m^3/ha	Mg/ha	Mg/ha	a	m^3/ha	Mg/ha	Mg/ha
Current recommendations	Current climate	36	43.6	8.0	7.3	62	85.4	15.7	10.4	–	–	–	–	84	357	65.4	36.4
	A2	30	45.2	8.3	7.6	56	84.3	15.5	9.2	–	–	–	–	75	481	88.5	46.6
Economical optimum	Current climate	48	34.7	6.4	4.4	62	40.2	7.4	4.7	–	–	–	–	80	386	71.2	35.6
	A2	25	22.5	3.8	5.3	43	33.5	5.7	4.3	49	12.1	2.1	1.7	54	326	55.5	33.5
No thinning	Current climate	–	–	–	–	–	–	–	–	–	–	–	–	150*	750*	142.4*	46.2*
	A2	–	–	–	–	–	–	–	–	–	–	–	–	150*	829*	186.6*	58.8*

* not harvested, but simulated status of the living trees at the age of 150 years.

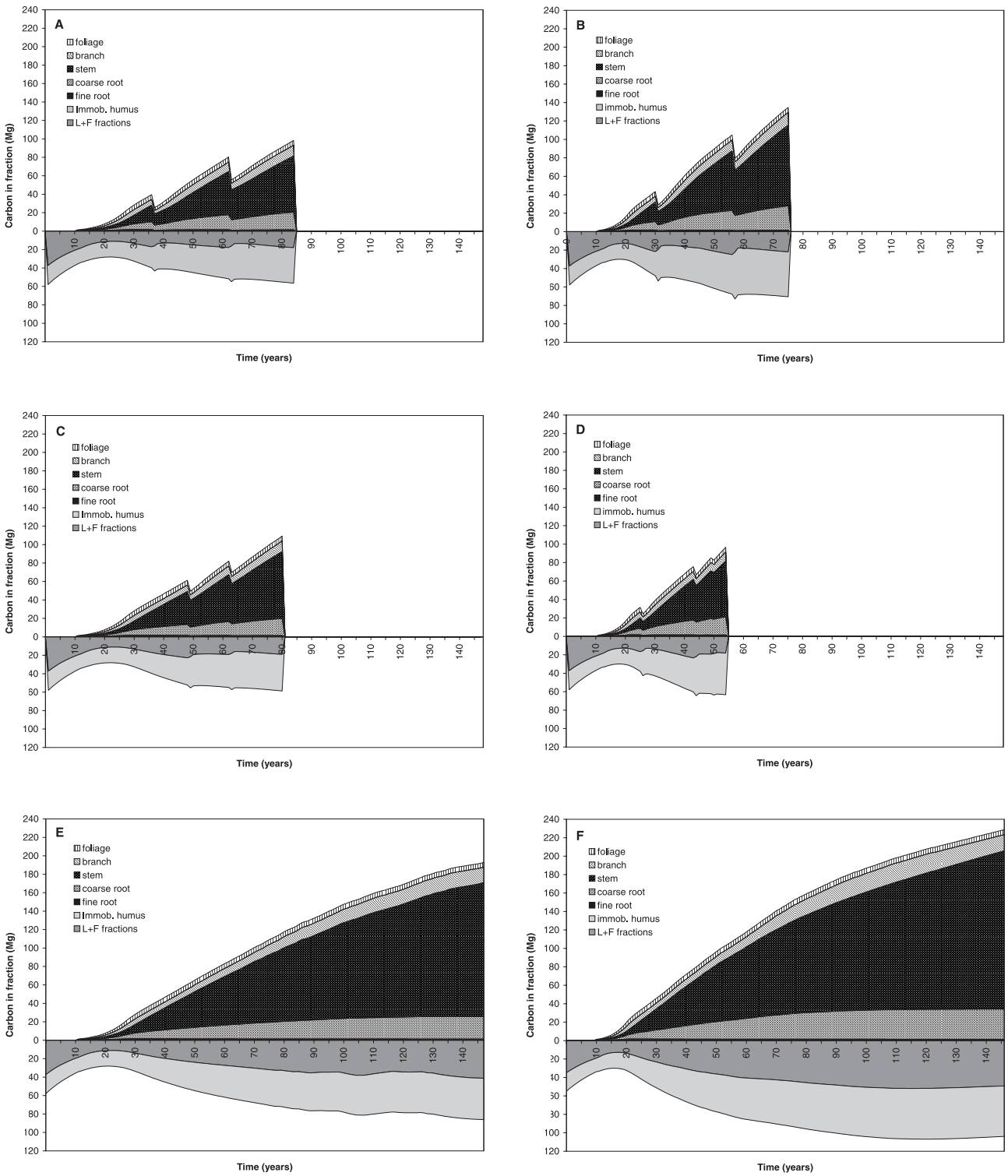


Fig. 4 The carbon stocks of biomass compartments and soil fractions with different management scenarios in the current (A, C, and E) and the changing climate (B, D, and F)

The simulated management scenarios were (i) thinnings and final harvesting according to the current recommendations (Tapio) (A and B), (ii) management practices based on economic optimization (C and D), and (iii) no management (E and F).

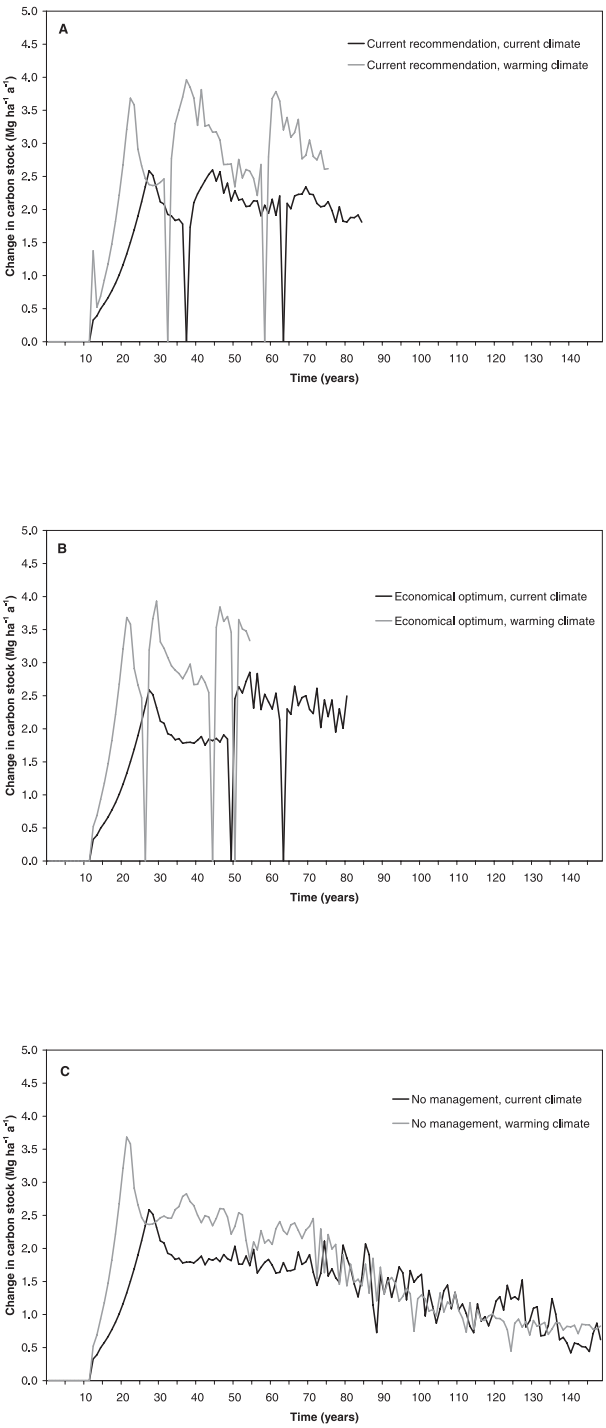


Fig. 5 The change in the biomass carbon stock under current and changing climate conditions with current management practices (A), management based on economic optimization (B), and no management (C)

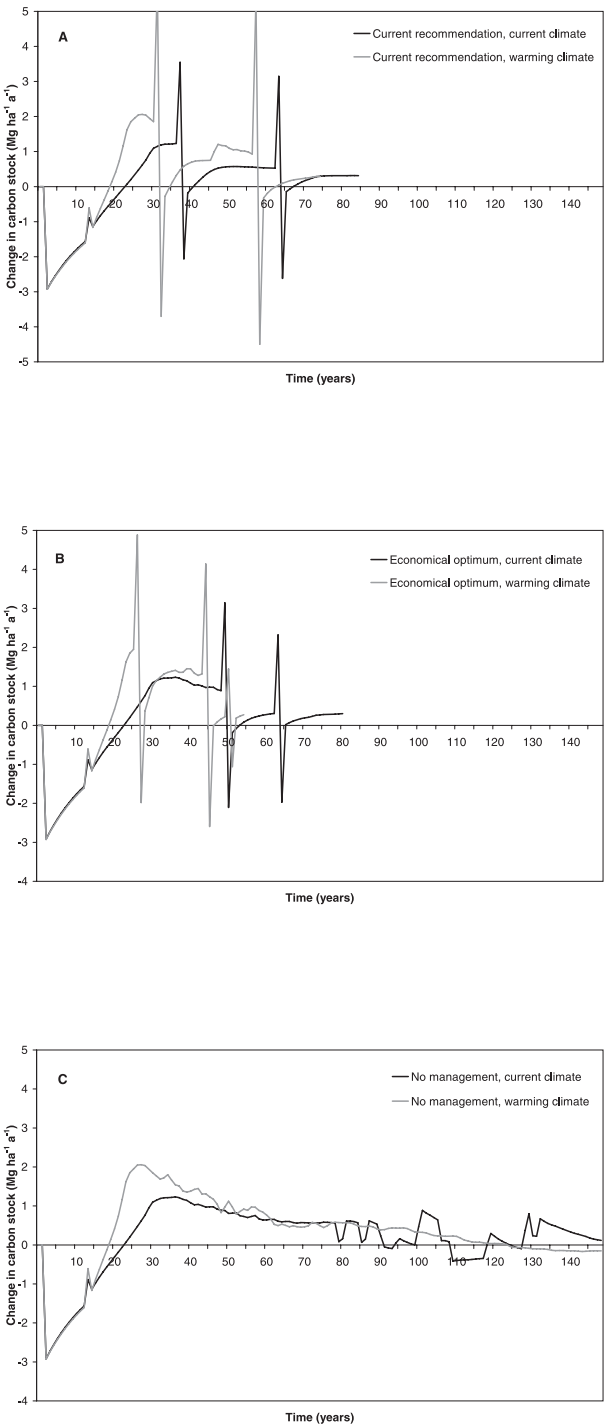


Fig. 6 The change in the soil carbon stock with different management scenarios under current and changing climate conditions

Management scenarios (A, B, and C) as in Fig 5.

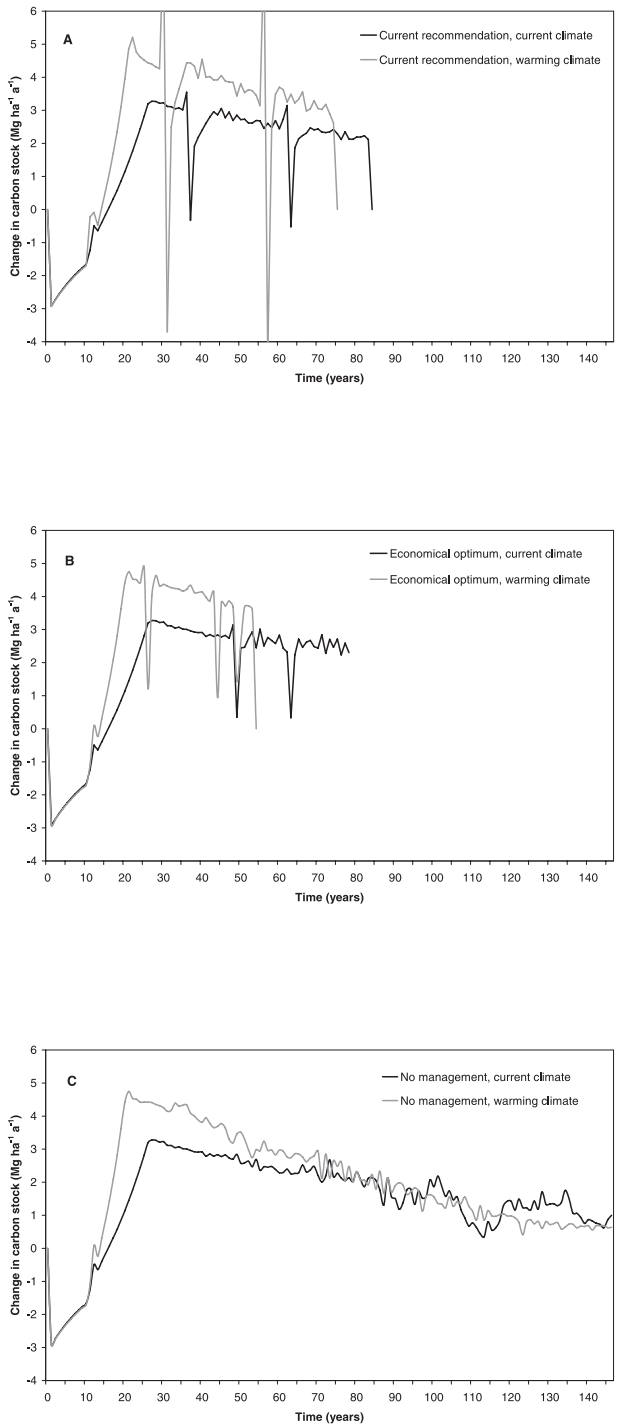


Fig. 7 The net change in the stand carbon stock (including both tree stand and soil) with different management scenarios under current and changing climate conditions
Management scenarios (A, B, and C) as in Fig 5.

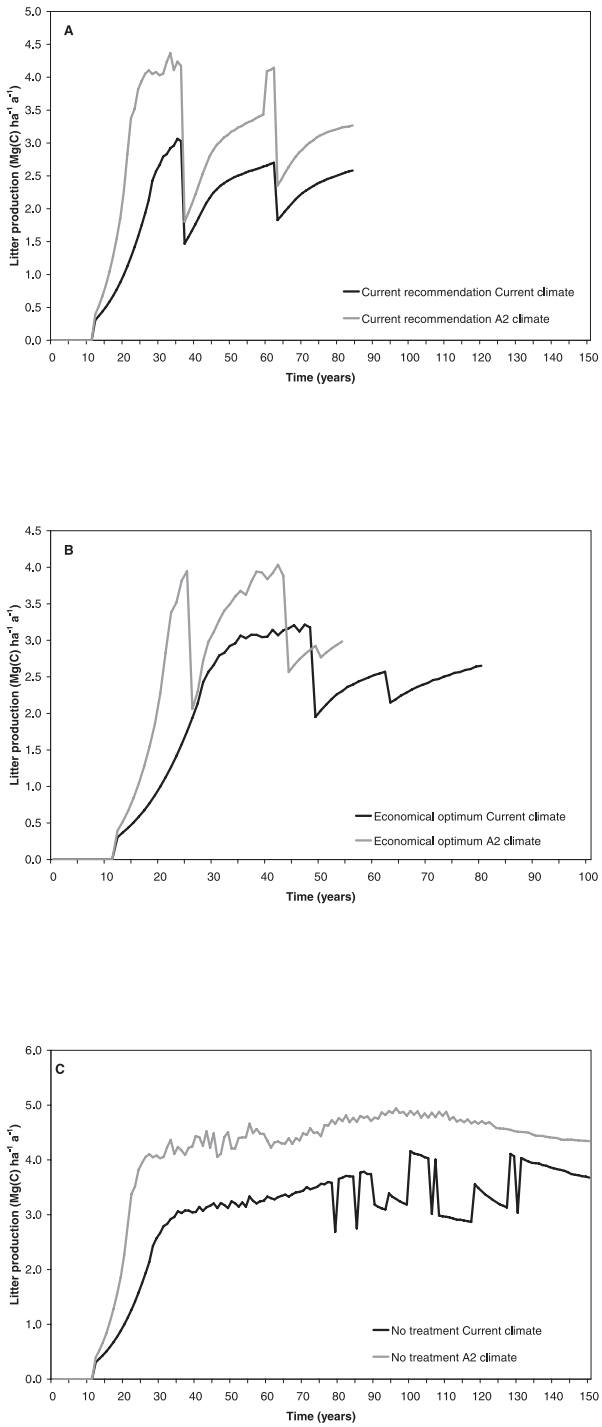


Fig. 8 The litter production with different management scenarios under current and changing climate conditions
Management scenarios (A, B, and C) as in Fig 5.

soil carbon stock tends to be higher than in the current climate (Fig. 6A-6C and Fig. 4).

Carbon Sequestration Affected by Management

In addition to the tendency of tree biomass accumulating with the stand age, the vegetation carbon stock was driven by the timing and the intensity of timber harvests. After commercial thinnings after the stand age of 40 years, the biomass carbon stocks with current management were 13 Mg/ha lower in comparison to the unmanaged stand (Fig. 4). Mature stands of both current and economically optimal management regime had lower biomass carbon stock than unmanaged forests at the same age (Fig. 4). Mature unmanaged forest was a carbon sink for entire simulation period of 150 years (Fig. 7C). The amount of carbon removed from the managed stands with harvested stem wood is lower than difference seen in the standing carbon stock between managed and unmanaged stands (Fig. 4, Table 1).

The economic optimization of thinnings resulted in a higher biomass of the carbon stock in the stands younger than 50 years and to a lower biomass in the older stands in comparison to the current management recommendations (Fig. 4). Length of the rotation period was shorter with the economically optimal management scenario, which resulted in lower average carbon stock of biomass over a rotation period. At the age of 70 years in the current climatic conditions, the biomass carbon stock was largest in the unmanaged stands (Fig. 4). Economically optimal thinnings resulted in a lower standing tree biomass and, a lower proportion of the biomass was allocated to the stem wood (Fig. 4).

The economically optimal thinning regime in the current climate resulted in relatively fast soil carbon sequestration until the first thinnings, but thereafter the soil carbon sink was very small (Fig. 4), because the flux of carbon from vegetation to soil (i.e., the amount of litter) was greatly reduced after removals (Fig. 8B, Table 1). The amount of produced litter tends to be low for a few years after thinnings with decreased amount of living trees, since the litter production is directly dependent on the standing biomass (Fig. 4, Fig. 8A-8C).

DISCUSSION

Our estimates of the average net primary production (NPP) (i.e., the rate of carbon bound in plant structures together with annual litter production) as well as the predicted amount of carbon in the vegetation and soil were consistent with earlier studies in boreal coniferous stands (Finér *et al.*, 2003; Liski *et al.*, 2001; Mäkipää *et al.*, 1999). In this study, a simulation was made for a spruce stand at a mesic site type, which is the most common site type (fertility class) in Southern Finland. Norway spruce is one of the dominant tree species in Northern Europe (Sykes and Prentice, 1995), and in Finland the majority of the mesic sites are spruce dominated (Reinikainen *et al.*, 2000). Thus, our simulations of Norway spruce stands reflect the potential climate responses of a large proportion of forests in Southern Finland.

In our simulations, Norway spruce had a positive growth response to the changing climate in an unmanaged stand as well as in a forest stand managed according to the current recommendations. A considerable increase in the net primary production (NPP) and in the net ecosystem exchange (NEE) of Norway spruce stands was also predicted by Bergh *et al.* (2005) and Jansson *et al.* (2008). In a review on forest growth in a changing climate, Kirschbaum (2000) concluded that growth has a positive response to increasing temperature, provided that adequate water is available, since photosynthesis is positively affected by a temperature increase. Additionally, the ratio of respiration to photosynthesis is not significantly altered with an increase in temperature. Briceño-Elizondo *et al.* (2006) simulated increased growth of Norway spruce with elevated temperature, but in Southern Finland this positive growth response was sensitive to concurrent reduction of precipitation. Earlier studies with a gap type ecosystem model have predicted an opposite (declining) trend in the growth of Norway spruce in a changing climate (e.g. Karjalainen, 1996; Kellomäki *et al.*, 2008), but the responses of tree species to temperature were based on a simple approximation of a multiplicative model from the biogeographical range of species distribution, which introduces large uncertainties into the model predictions (see Austin, 1992). The simulated positive growth response to an increase in temperature is consistent with analyses of increment chronologies, which have shown that the growth of Norway spruce is positively related to temperature in a wide range of temperatures (e.g. Miina, 2000; Mäkinen *et al.*, 2000). Some negative relationship is seen only with Norway spruce growth and the temperatures of previous July and August (Miina, 2000), which results from enhanced flowering of Norway spruce that decreases growth in the following year (Pukkala, 1987).

According to our simulations, the carbon accumulation in the forest soil was increased in the changing climate. The increase in the soil carbon stock as a result of increased temperature and precipitation was also reported by Cao and Woodward (1998) and Karjalainen *et al.* (2003). However, some studies with a gap type ecosystem model (Mäkipää *et al.*, 1999) and with a dynamic soil carbon model combined to a forest scenario model (Karjalainen *et al.*, 2002) have also reported an opposite trend. Jansson *et al.* (2008) simulated ecosystem responses to a climate change with a coupled ecosystem model that included feedbacks of nitrogen cycling, and they found only small changes in soil carbon of Norway spruce stands in Sweden. In our simulations, a positive response of soil carbon to a climate change was mainly due to the increased biomass production and the resulting increase in the litter input to the forest soil. Our stand growth model may underestimate natural mortality, which would lead to a slightly overestimated biomass production and an underestimated input of dead wood into the soil. On the other hand, our current implementation of

the ROMUL model does not consider the effect of log dimensions to the rate of decomposition, and therefore in the current results, the decomposition rate of tree stems is overestimated. The slower rate of stem wood decomposition may well overcome the effect of underestimated mortality.

In the simulations of the changing climate, the rate of decomposition was increased, but the increase in the litter production was even larger. Thus, our results suggest that boreal forest soils may act as carbon sinks also in the changing climate, provided that the balance between the litter produced by standing biomass and the rate of decomposition remains sustainable. A positive feedback between nitrogen availability and enhanced growth of trees followed by increased litter production may further increase the carbon sink potential of the stand biomass and soil carbon stocks of boreal conifer stands in the changing climate (see also JANSSON *et al.*, 2008). The potential enhancement of growth due to the increased availability of nitrogen will be introduced to our model in the next development phases.

In the simulation of the managed forests, vegetation acted as a carbon sink excluding the times of harvest, but the carbon sink in managed forests was smaller than that in the unmanaged stands. Decline in soil carbon stock for the first two decades after a clear-cutting was followed by a continuous soil carbon sequestration in the unmanaged stand, but in the managed stands soil was a carbon source for some years after the thinnings. Heavy thinnings can turn forest soil to a net carbon source for some years after treatments. The decreasing trend of soil carbon stock can be strengthened, if heavy thinnings are continued over several rotation periods. Short rotation periods may also decrease site productivity (SEELY *et al.*, 2002). According to our simulations, the forest carbon stock was at its largest in the unmanaged forests and unmanaged stands were net carbon sinks also in the end of the simulation at the age of 150 years. The result is consistent with a number of previous reports; e.g., COOPER (1983), THORNLEY and CANNELL (2000), MIKHAILOV *et al.* (2004), SCHMID *et al.* (2006) and ERIKSSON (2006) have reported that unmanaged forests store more carbon than their managed counterparts. In addition, GARCIA-GONZALO *et al.* (2007) have shown that shifting to thinning regimes that allowed a higher stocking density of trees resulted in an increase in carbon sequestration. Based on simulations with a process-based model, LASCH *et al.* (2005) have concluded that long rotation combined with a low thinning intensity is the best management scenario, if the objective is to maximize carbon sequestration in temperate pine-broadleaved forests.

Climate change will greatly affect forest ecosystems and their carbon sequestration potential, but in managed forests carbon accumulation is also strongly driven by management decisions. Sustainability of alternative management regimes has to be considered from both ecological and economical aspects before science based recommendations for management in changing environment can be launched. The conflict between carbon management, and management to optimize the economic values of forestry was already demonstrated by ERIKSSON (2006), who concluded that a strategy with no thinning, which would maximize the carbon pool, would not be ideal from an economic perspective. A future challenge is to link biodiversity measures and economical optimization routines to the model. We conclude that simulations with the process-based forest growth model together with a soil model can be of help in developing ecologically and economically sustainable management practices.

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Appendix 1 Equations of the ROMUL decomposition model as reported by CHERTOV *et al.* (2007) and daily variation of temperature and soil moisture

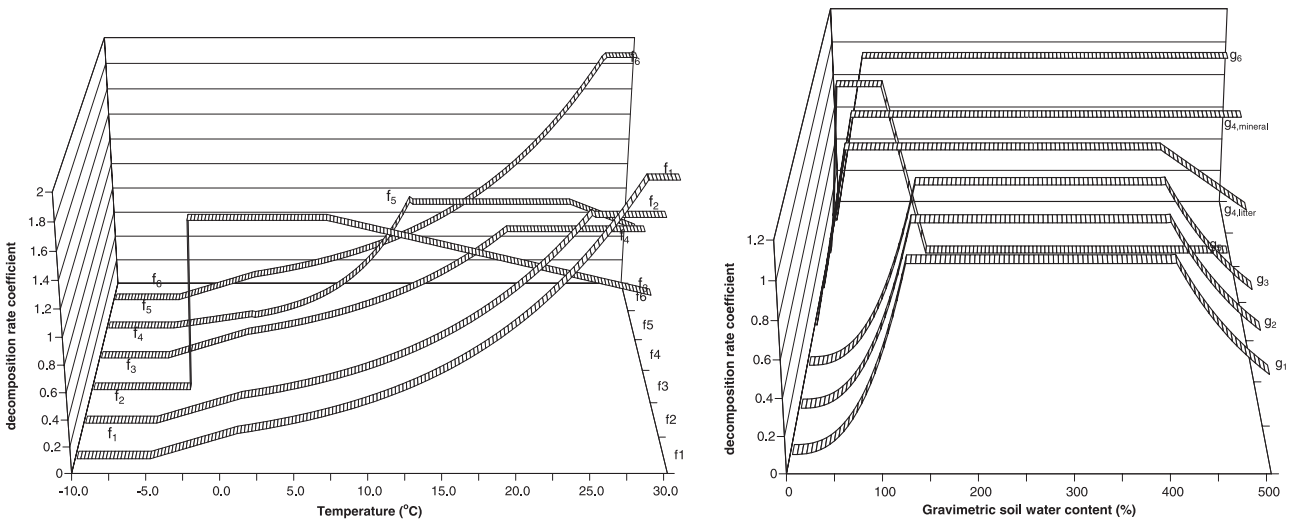

Fig. A1 Temperature and moisture dependencies of the soil fluxes

The sub-indices of the functions refer to the corresonding *k*-factors, i.e. the coefficient k_3 of mass flow (from *Lx,i* fraction to *Fx,i* fraction) is adjusted with the temperature coefficient f_3 and the soil moisture coefficient g_3.

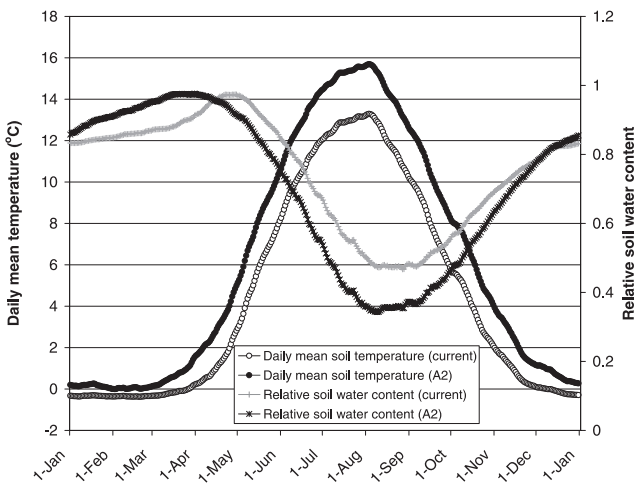

Fig. A2 Variation of the daily temperature and relative soil moisture content in the current and changing climate

Article

Developing Forest Models from Longitudinal Data: A Case Study Assessing the Need to Account for Correlated and/or Heterogeneous Error Structures under a Nonlinear Mixed Model Framework

Shongming Huang*, Yuqing Yang* and Shawn X. Meng*

ABSTRACT

In this study we demonstrated the procedures for model estimation and prediction based on the nonlinear mixed model (NLMM) technique. Since the unequally spaced and unbalanced longitudinal data used to fit forest models are often correlated and unequally varied, generalized error structures were examined and compared to the independent and identically distributed (iid) structure. In addition, since the vast majority of forest models are developed to be used as predictive tools on new data once the model coefficients have been estimated, predictions from the fitted model with and without accounting for the generalized error structures were evaluated on both model fitting and independent model validation data sets. Results showed that, under the NLMM framework, the iid structure is a superior choice for addressing correlated and heteroscedastic errors, provided that the model is appropriate for the data. This outcome has important practical implications, as a simpler error structure can achieve better predictions than more complex structures. The theoretical and practical consequences of ignoring or accounting for the error structure in NLMM estimation and prediction are discussed.

Keywords: error covariance structure, correlation, heteroscedasticity, mixed model prediction

INTRODUCTION

Forest modelers have used the nonlinear mixed-effects modeling technique popular in pharmacokinetics, epidemiology, and statistics to develop nonlinear mixed models (NLMMs) for predicting forest growth and yield. These models have become the essential tools in growth and yield studies, and their use is increasingly common (Gregoire and Schabenberger, 1996; Trincado and Burkhart, 2006; Temesgen *et al.*, 2008; Meng *et al.*, 2008; Huang *et al.*, 2009c; Yang *et al.*, 2009; Meng and Huang, 2010). NLMMs contain both fixed and random parameters, where the fixed parameters are common to all subjects and the random parameters are unique for each subject within the population. Because of the inclusion of subject-specific (SS) random parameters, a NLMM essentially provides a localized fit to each and every subject in the population. This localized fit is supplemented during the estimation process by the information about the entire population, effectively allowing subject i to "borrow strength" across all subjects to get the best local predictions (Davidian and Giltinan, 1995).

NLMMs are often developed based on longitudinal data, which can be correlated and heteroscedastic within the same or amongst different subjects, as oppose to independent and identically distributed (iid). The heteroscedasticity could take different forms, and the correlation could be both spatial and temporal (e.g., serially- or auto-correlated within the same subject and contemporaneously-correlated amongst different subjects). Although the NLMM method can alleviate the non-iid problem, it may not entirely remove it (e.g., Hall and Clutter, 2004). From a theoretical standpoint, if the non-iid errors are not appropriately accounted for during estimation, it could invalidate inferences (hypothesis testing and interval estimation) for the estimated model coefficients, notwithstanding the coefficients are still unbiased (Judge *et al.*, 1988).

Despite the repeated calls by statisticians to address the correlation and heteroscedasticity issue for inference purposes, many forest modelers eschewed the issue for various reasons. They developed models assuming the iid structure without even considering if it was appropriate or not, then used the models to make predictions on new data irrespective of the error

Corresponding author: Shongming Huang
E-mail: Shongming.huang@gov.ab.ca
* Forest Management Branch, Alberta Department of Sustainable Resource Development, 8th Floor, 9920-108 Street, Edmonton, Alberta, Canada T5K 2M4

structure. On the other hand, some modelers invoked the issue as soon as repeated measurement data were involved, believing that accounting for the non-iid errors was a priori for any meaningful model building. Still there are some other modelers who took a more ambivalent approach towards the issue. They extolled the necessities and virtues of addressing the issue in selected studies, only to ignore or circumvent it in other studies. Comparison of the models estimated with and without assuming the iid error structure was not done often, especially with regard to model predictions under different error structures, and on independent validation data not used in modeling.

The primary objectives of this study were to: 1) compare model estimation and prediction with and without accounting for the correlated and heterogeneous errors under the NLMM framework, and 2) assess the need to account for non-iid errors when developing nonlinear mixed forest models, and when using the developed models to make prediction on new data.

NONLINEAR MIXED MODEL ESTIMATION

A general expression for NLMMs can be written as (VONESH and CHINCHILLI, 1997):

$$\boldsymbol{y}_i = f(\boldsymbol{x}_i, \boldsymbol{\beta}, \boldsymbol{b}_i) + \boldsymbol{\varepsilon}_i \qquad (i = 1, 2, \ldots, m) \tag{1}$$

where $\boldsymbol{y}_i = [y_{i1}, y_{i2}, \ldots, y_{in_i}]'$ is a vector of measurements on subject i with n_i observations, f is some nonlinear function, $\boldsymbol{x}_i$ is a known design matrix of covariates, $\boldsymbol{\beta}$ is a $(p\times1)$ vector of fixed parameters common to all subjects, $\boldsymbol{b}_i$ is a $(q\times1)$ vector of random parameters unique for the ith subject, and $\boldsymbol{\varepsilon}_i = [\varepsilon_{i1}, \varepsilon_{i2}, \ldots, \varepsilon_{in_i}]'$ is a vector of within-subject errors. The $\boldsymbol{b}_i$ and $\boldsymbol{\varepsilon}_i$ are usually assumed to be uncorrelated and normally distributed with mean zero and variance-covariance matrices $\boldsymbol{D}$ and $\boldsymbol{R}_i$, respectively, that is, $\boldsymbol{b}_i \sim N(\boldsymbol{0}, \boldsymbol{D})$ and $\boldsymbol{\varepsilon}_i \sim N(\boldsymbol{0}, \boldsymbol{R}_i)$.

Different methods have been developed to estimate the parameters of Eq. (1) (VONESH and CHINCHILLI, 1997). The generalized least squares estimator $\hat{\boldsymbol{\beta}}$ of the $\boldsymbol{\beta}$ and the random parameters predictor $\hat{\boldsymbol{b}}_i$ of the $\boldsymbol{b}_i$ in Eq. (1) can be obtained as described in FITZMAURICE *et al.* (2004):

$$\hat{\boldsymbol{\beta}} = \left(\sum_{i=1}^{m} \boldsymbol{X}_i'(\boldsymbol{Z}_i\hat{\boldsymbol{D}}\boldsymbol{Z}_i' + \hat{\boldsymbol{R}}_i)^{-1}\boldsymbol{X}_i \right)^{-1} \sum_{i=1}^{m} \boldsymbol{X}_i'(\boldsymbol{Z}_i\hat{\boldsymbol{D}}\boldsymbol{Z}_i' + \hat{\boldsymbol{R}}_i)^{-1}\boldsymbol{y}_i^* \tag{2}$$

$$\hat{\boldsymbol{b}}_i = \hat{\boldsymbol{D}}\boldsymbol{Z}_i'\hat{\boldsymbol{V}}_i^{-1}(\boldsymbol{y}_i^* - \boldsymbol{X}_i\hat{\boldsymbol{\beta}}) \tag{3}$$

where $\boldsymbol{X}_i$ and $\boldsymbol{Z}_i$ are derivatives of $\boldsymbol{y}_i$ with respect to $\boldsymbol{\beta}$ and $\boldsymbol{b}_i$, respectively, $\hat{\boldsymbol{D}}$ and $\hat{\boldsymbol{R}}_i$ are estimates of $\boldsymbol{D}$ and $\boldsymbol{R}_i$ respectively, and $\hat{\boldsymbol{V}}_i = Var(\boldsymbol{y}_i^*) = \boldsymbol{Z}_i\hat{\boldsymbol{D}}\boldsymbol{Z}_i' + \hat{\boldsymbol{R}}_i$ is the estimated variance-covariance for the "pseudo-response" function $\boldsymbol{y}_i^*$. More specific expressions of $\hat{\boldsymbol{b}}_i$ for the first-order (FO) method of BEAL and SHEINER (1982) and first-order conditional expectation (FOCE) method of LINDSTROM and BATES (1990) can be written as follows:

$$\hat{\boldsymbol{b}}_i = \hat{\boldsymbol{D}}\boldsymbol{Z}_i'(\boldsymbol{Z}_i\hat{\boldsymbol{D}}\boldsymbol{Z}_i' + \hat{\boldsymbol{R}}_i)^{-1}[\boldsymbol{y}_i - f(\boldsymbol{x}_i, \hat{\boldsymbol{\beta}}, \boldsymbol{0})] \text{(FO)} \tag{4}$$

$$\hat{\boldsymbol{b}}_i = \hat{\boldsymbol{D}}\boldsymbol{Z}_i'(\boldsymbol{Z}_i\hat{\boldsymbol{D}}\boldsymbol{Z}_i' + \hat{\boldsymbol{R}}_i)^{-1}[\boldsymbol{y}_i - f(\boldsymbol{x}_i, \hat{\boldsymbol{\beta}}, \hat{\boldsymbol{b}}_i) + \boldsymbol{Z}_i\hat{\boldsymbol{b}}_i] \text{(FOCE)} \tag{5}$$

A summary of the FO and FOCE methods in a forestry context is provided in HUANG *et al.* (2009a), and MENG and HUANG (2009). For FOCE, because $\hat{\boldsymbol{b}}_i$ appears on both sides of Eq. (5), it must be solved numerically (LINDSTROM and BATES, 1990; SCHABENBERGER, 1994; TEMESGEN *et al.*, 2008; MENG *et al.*, 2008), to avoid a potential bias (MENG and HUANG, 2009).

In model estimation, it is common to assume that the covariance matrix $\boldsymbol{D}$ for the random parameters represents the variability and correlations among the subjects (DAVIDIAN and GILTINAN, 1995; PINHEIRO and BATES, 2004). For instance, for a model with three random parameters:

$$\boldsymbol{D} = \begin{bmatrix} \sigma_{b_1}^2 & \sigma_{b_1b_2} & \sigma_{b_1b_3} \\ & \sigma_{b_2}^2 & \sigma_{b_2b_3} \\ & & \sigma_{b_3}^2 \end{bmatrix} \tag{6}$$

where $\sigma_{b_1}^2$, $\sigma_{b_2}^2$ and $\sigma_{b_3}^2$ are the variances for the random parameters (b_1, b_2, b_3), and $\sigma_{b_1b_2}$, $\sigma_{b_1b_3}$ and $\sigma_{b_2b_3}$ are the covariances between pairs of random parameters. Typically, $\boldsymbol{D}$ is also assumed to be the same for each and every subject within the population of m subjects.

As for the error covariance structure $\boldsymbol{R}_i$ it must be specified according to the nature of the data. For homoscedastic and uncorrelated data, the errors are iid. Therefore, $\boldsymbol{R}_i = \sigma^2\boldsymbol{I}_{n_i} = \sigma^2\boldsymbol{I}$, where σ^2 is the error variance and $\boldsymbol{I}_{n_i}$ or $\boldsymbol{I}$ represents an $n_i\times n_i$ identity matrix.

When the data are uncorrelated but heteroscedastic, the $\boldsymbol{R}_i$ for the banded main diagonal heterogeneous error structure UN(1) for a subject of three observations, can be written as:

$$\boldsymbol{R}_i = \begin{bmatrix} \sigma_1^2 & 0 & 0 \\ & \sigma_2^2 & 0 \\ & & \sigma_3^2 \end{bmatrix} = \text{UN (1)} \tag{7}$$

where σ_1^2, σ_2^2 and σ_3^2 are variances associated with observations 1, 2 and 3, respectively. Often, the variances (σ_i^2s) can be expressed as a linear or nonlinear function f of the predicted $\boldsymbol{y}_i$ ($\hat{\boldsymbol{y}}_i$) and/or the $\boldsymbol{x}_i$ variable(s) in the following forms:

$$\sigma_i^2 = \sigma^2 x_{ij}^{\lambda} \quad \sigma_i^2 = \sigma^2 \hat{y}_{ij}^{\lambda} \quad \sigma_i^2 = \sigma^2 X_i^k x_{ij}^{\lambda} \quad \sigma_i^2 = \sigma^2 X_i^k \hat{y}_{ij}^{\lambda}$$
$$\sigma_i^2 = f(X_i, x_{ij}, \hat{y}_{ij}) \tag{8}$$

where k and λ are constants, and X_i is the x-variable(s) used to reflect remnant between-subject variation (HUANG *et al.*, 2009a). The first four variance forms in Eq. (8) and other forms such as $\sigma_i^2 = a_0 X_i^{a_1} \hat{y}_{ij}^{a_2} x_{ij}^{a_3}$, where $a_0 - a_3$ are parameters to be estimated, can all be thought as special cases of the last form in Eq. (8). Once the variance form is identified, a weighting factor (W) chosen inversely proportional to the variance function is applied in model fitting. In SAS, for instance, $W = 1/x_{ij}^{\lambda} = x_{ij}^{-\lambda}$ when $\sigma_i^2 = \sigma^2 x_{ij}^{\lambda}$, and $W = X_i^{-k}\hat{y}_{ij}^{-\lambda}$ when $\sigma_i^2 = \sigma^2 X_i^k \hat{y}_{ij}^{\lambda}$.

If the data are correlated but homoscedastic, various $\boldsymbol{R}_i$s can be specified. To account for the unequally spaced and unbalanced nature of the forest data, we focused on the seven spatial covariance structures (SAS INSTITUTE INC., 2004; LITTELL *et al.*, 2006; YANG and HUANG, 2008). Two examples, the spatial power (SP(pow)) and the spatial linear (SP(lin)), are given here:

$$\boldsymbol{R}_i = \sigma^2 \boldsymbol{\Psi} = \sigma^2 \begin{bmatrix} 1 & \rho^{d_{12}} & \rho^{d_{13}} \\ & 1 & \rho^{d_{23}} \\ & & 1 \end{bmatrix} = \text{SP(pow)} \tag{9}$$

$$\boldsymbol{R}_i = \sigma^2 \boldsymbol{\Psi} = \sigma^2 \begin{bmatrix} 1 & (1-\rho d_{12}) & (1-\rho d_{13}) \\ & 1 & (1-\rho d_{23}) \\ & & 1 \end{bmatrix} = \text{SP(lin)} \tag{10}$$

where $\boldsymbol{\Psi}$ is the correlation matrix, d_{st} is the distance between two measurements at times s and t ($d_{st} = |t_s - t_t|$), and ρ is the correlation parameter.

When the data are both correlated and heteroscedastic, the aforementioned covariance structures for $\boldsymbol{R}_i$ can be combined in various forms depending on the weighting factor. As an example, recognizing the correlation-covariance relationship $\rho_{ij} = \sigma_{ij}/(\sigma_i \sigma_j)$ and expanding the SP (pow) in Eq. (9) to include the heteroscedastic errors $\sigma_i^2 = \sigma^2 x_{ij}^{\lambda}$ defined in Eq. (8), produce the $\boldsymbol{R}_i$ that accounts for both correlation and heteroscedasticity:

$$\boldsymbol{R}_i = \sigma^2 \begin{bmatrix} x_{i1}^{\lambda} & x_{i1}^{\lambda/2} x_{i2}^{\lambda/2} \rho^{d_{12}} & x_{i1}^{\lambda/2} x_{i3}^{\lambda/2} \rho^{d_{13}} \\ & x_{i2}^{\lambda} & x_{i2}^{\lambda/2} x_{i3}^{\lambda/2} \rho^{d_{23}} \\ & & x_{i3}^{\lambda} \end{bmatrix}. \tag{11}$$

If $\sigma_i^2 = \sigma^2 \hat{y}_{ij}^{\lambda}$, a different $\boldsymbol{R}_i$ with x_{ij} replaced by the respective $\hat{y}_{ij}$, can be derived. Other more complex weighting factors can be incorporated into different correlation structures to form $\boldsymbol{R}_i s$ in a similar manner. A more generalized unstructured (UN) $\boldsymbol{R}_i$ structure takes the following form:

$$\boldsymbol{R}_i = \begin{bmatrix} \sigma_1^2 & \sigma_{12} & \sigma_{13} \\ & \sigma_2^2 & \sigma_{23} \\ & & \sigma_3^2 \end{bmatrix} = \text{UN} \tag{12}$$

where σ_{12}, σ_{13} and σ_{23} are covariances. Although in theory, the generalized UN structure is most flexible and could lead to a better fit, provided that the data and the specified model allow for the fit, in practice, because more parameters need to be estimated from the reduced degrees of freedom, the UN structure may not achieve convergence (which was repeatedly encountered on the data used in this study). This is similar to the concept of over-fitting or over-parameterization in nonlinear regression analysis. There are considerable dangers in specifying and estimating too many parameters when fewer may work (e.g., a 3-parameter Chapman-Richards function may work much better than a 4-parameter counterpart for many forestry data sets).

All model fittings in this study were carried out using the SAS macro %NLINMIX (SAS INSTITUTE INC., 2004; LITTELL *et al.* 2006). The default fittings assume the iid structure. For fittings associated with heteroscedastic and correlated error structures, an expression of WEIGHT and the keyword TYPE within the REPEATED statement must be specified accordingly.

To assess the goodness-of-fit (GOF) of a NLMM on model fitting data, three types of criteria detailed in HUANG *et al.* (2009b) were used in addition to significant model parameters:
1) Akaike information criterion (AIC) and the Schwarz's Bayesian information criterion (BIC):

$$\text{AIC} = -2\ln(L) + 2P \qquad \text{BIC} = -2\ln(L) + P\ln(m) \tag{13}$$

where L is the maximum likelihood, P is number of parameters, and m is number of subjects.
2) Scatter and trajectory plots of ordinary, studentized, lagged, and normalized residuals; and frequency distribution plots of residuals and other statistics calculated by subject.
3) Plot of observed versus predicted values across the entire x-range where predictions are likely to be made in model applications (i.e., "spaghetti" or "chow-mein" plot). The fit and diagnostic statistics and the associated plots mostly reveal model GOF within the observed data range, and this is not enough for predictive NLMMs (SHEINER and WAKEFIELD, 1999; HUANG *et al.*, 2009b). The spaghetti plot fills in the gaps left by the statistics and other types of plots. It provides a powerful tool in exposing model behaviors, not only within but also outside the observed data range.

MODEL PREDICTIONS UNDER IID, CORRELATED AND GENERALIZED ERROR STRUCTURES

For a NLMM with an iid error structure, once the $\hat{\boldsymbol{\beta}}$ and $\hat{\boldsymbol{b}}_i$ are known, the predicted $\boldsymbol{y}_i$ ($\hat{\boldsymbol{y}}_i$) for subject i can be obtained for the FO and FOCE methods (VONESH and CHINCHILLI, 1997):

$$\hat{\boldsymbol{y}}_i = f(\boldsymbol{x}_i, \hat{\boldsymbol{\beta}}, \boldsymbol{0}) + \boldsymbol{Z}_i \hat{\boldsymbol{b}}_i \text{(FO)} \tag{14}$$

$$\hat{\boldsymbol{y}}_i = f(\boldsymbol{x}_i, \hat{\boldsymbol{\beta}}, \hat{\boldsymbol{b}}_i) \text{ (FOCE)} \tag{15}$$

For NLMMs with correlated or generalized error structures, adjusted predictions that account for the correlated or generalized error structures can be derived following the general prediction theory (GOLDBERGER, 1962; JUDGE *et al.*, 1988). Here, only the final formulas for obtaining the $\hat{\boldsymbol{y}}_i$ for NLMMs are shown (HUANG *et al.*, 2009a; MENG and HUANG, 2010):

$$\hat{\boldsymbol{y}}_{0i} = f(\boldsymbol{x}_{0i}, \hat{\boldsymbol{\beta}}, \boldsymbol{0}) + \boldsymbol{Z}_{0i}\hat{\boldsymbol{b}}_i + \boldsymbol{V}'\boldsymbol{\Psi}^{-1}\left[\hat{\boldsymbol{y}}_i - f(\boldsymbol{x}_i, \hat{\boldsymbol{\beta}}, \boldsymbol{0}) - \boldsymbol{Z}_i\hat{\boldsymbol{b}}_i\right] \text{(FO)} \tag{16}$$

$$\hat{\boldsymbol{y}}_{0i} = f(\boldsymbol{x}_{0i}, \hat{\boldsymbol{\beta}}, \hat{\boldsymbol{b}}_i) + \boldsymbol{V}'\boldsymbol{\Psi}^{-1}\left[\hat{\boldsymbol{y}}_i - f(\boldsymbol{x}_i, \hat{\boldsymbol{\beta}}, \hat{\boldsymbol{b}}_i)\right] \text{(FOCE)} \tag{17}$$

where $\hat{\boldsymbol{y}}_{0i}$, $\boldsymbol{x}_{0i}$, and $\boldsymbol{Z}_{0i}$ refer to the variables associated with future observations, $\boldsymbol{V}$ contains the correlations between the past and future errors, and $\boldsymbol{\Psi}$ is the correlation matrix of past errors.

Using the SP(pow) in Eq. (9) as an example, if only one past observation was used to make future predictions, $\boldsymbol{\Psi}=1$, and the correlations between the past and future errors d_{12}, d_{13}, $\cdots$, d_{1k} distance apart is $\boldsymbol{V}=[\rho^{d_{12}}, \rho^{d_{13}}, \cdots, \rho^{d_{1k}}]$. If three past observations are used, the $\boldsymbol{\Psi}$ and $\boldsymbol{V}$ are:

$$\boldsymbol{\Psi}=\begin{bmatrix}1 & \rho^{d_{12}} & \rho^{d_{13}}\\ \rho^{d_{12}} & 1 & \rho^{d_{23}}\\ \rho^{d_{13}} & \rho^{d_{23}} & 1\end{bmatrix} \qquad \boldsymbol{V}=\begin{bmatrix}\rho^{d_{14}} & \rho^{d_{15}} & \cdots & \rho^{d_{1k}}\\ \rho^{d_{24}} & \rho^{d_{25}} & \cdots & \rho^{d_{2k}}\\ \rho^{d_{34}} & \rho^{d_{35}} & \cdots & \rho^{d_{3k}}\end{bmatrix}. \tag{18}$$

If in addition to correlation, heteroscedasticity also occurs, then the $\boldsymbol{\Psi}$ and $\boldsymbol{V}$ are expanded further to become, for instance,

$$\boldsymbol{\Psi}=\begin{bmatrix}x_{i1}^{\lambda} & x_{i1}^{\lambda/2}x_{i2}^{\lambda/2}\rho^{d_{12}}\\ & x_{i2}^{\lambda}\end{bmatrix}$$
$$\boldsymbol{V}=\begin{bmatrix}x_{i1}^{\lambda/2}x_{i3}^{\lambda/2}\rho^{d_{13}} & x_{i1}^{\lambda/2}x_{i4}^{\lambda/2}\rho^{d_{14}} & \cdots & x_{i1}^{\lambda/2}x_{ik}^{\lambda/2}\rho^{d_{1k}}\\ x_{i2}^{\lambda/2}x_{i3}^{\lambda/2}\rho^{d_{23}} & x_{i2}^{\lambda/2}x_{i4}^{\lambda/2}\rho^{d_{24}} & \cdots & x_{i2}^{\lambda/2}x_{ik}^{\lambda/2}\rho^{d_{2k}}\end{bmatrix} \tag{19}$$

for the variance function $\sigma_i^2=\sigma^2 x_{ij}^{\lambda}$ and using two past observations to make future predictions.

The $\boldsymbol{\Psi}$s and $\boldsymbol{V}$s for other number of past observations can be expanded in a similar manner. If a more complex variance function is involved, e.g., $\sigma_i^2=\sigma^2 X_i^k \hat{y}_{ij}^{\lambda}$ as in Eq. (8), the $\boldsymbol{\Psi}$ and $\boldsymbol{V}$ can be expanded accordingly, as shown below using one past observation as an example:

$$\boldsymbol{\Psi}=X_i^k\hat{y}_{ij}^{\lambda} \quad \boldsymbol{V}=[X_i^k\hat{y}_{i1}^{\lambda/2}\hat{y}_{i2}^{\lambda/2}\rho^{d_{12}} \;\; X_i^k\hat{y}_{i1}^{\lambda/2}\hat{y}_{i3}^{\lambda/2}\rho^{d_{13}} \;\; \cdots \;\; X_i^k\hat{y}_{i1}^{\lambda/2}\hat{y}_{ik}^{\lambda/2}\rho^{d_{1k}}]. \tag{20}$$

It is rather straightforward to show that the $\boldsymbol{\Psi}$s and $\boldsymbol{V}$s based on more past observations, and for other variance and covariance structures, can be derived in a similar manner.

GOODNESS-OF-PREDICTION MEASURES

Prediction in forestry typically refers to the prediction on new data not used in modeling, after a model has already been fitted. In this study, prediction was also done on the modeling data, in which the residuals and model fitting statistics should be identical to the prediction errors and prediction statistics if the NLMM estimation and prediction procedures are consistent. Four prediction statistics were calculated to evaluate the goodness-of-prediction of a fitted NLMM:

$$\bar{e}=\frac{1}{N}\sum_{i=1}^{m}\sum_{j=1}^{n_i}e_{ij} \qquad |\bar{e}|=\frac{1}{N}\sum_{i=1}^{m}\sum_{j=1}^{n_i}|e_{ij}|$$

$$SD=\sqrt{\frac{1}{(N-1)}\sum_{i=1}^{m}\sum_{j=1}^{n_i}(e_{ij}-\bar{e})^2} \qquad \delta=\bar{e}^2+SD^2 \tag{21}$$

where $\bar{e}$ is the mean bias, $|\bar{e}|$ is the mean absolute bias, SD is the standard deviation, δ is an overall accuracy measure (Cochran 1977), and N is the total number of observations from m subjects. Other goodness-of-prediction statistics could also be calculated (e.g., Hahn and Meeker, 1991; Huang *et al.*, 2009b). But those given in Eq. (21) appeared more common.

The plotting of prediction errors and prediction statistics was done both for the modeling data and model validation data. The spaghetti plots of the prediction trajectories across the entire x-range where predictions are likely to be made in model applications were examined carefully.

A CASE STUDY

This case study uses the white spruce (*Picea glauca*) volume-age data collected over the last 45 years from 600 permanent sample plots (PSPs) (Alberta Forest Service, 2000). The first 465 plots with 2,013 measurements were used for model fitting (Fig. 1(a)), and the remaining 135 plots with 486 measurements were used for model prediction (Fig. 2(a)).

Based on a detailed examination of the overall and SS volume-age trends exhibited by the data, a NLMM was chosen for the data:

$$\boldsymbol{Vol}_i=(\beta_1+b_{1i})\boldsymbol{Age}_i^{(\beta_2+b_{2i})}\exp[-(\beta_1+b_{1i})\boldsymbol{Age}_i]+\boldsymbol{\varepsilon}_i \tag{22}$$

where $\boldsymbol{Vol}_i$ and $\boldsymbol{Age}_i$ are observed volumes and ages for the ith plot, $\beta_1-\beta_2$ are fixed parameters, and $b_{1i}-b_{2i}$ are random parameters. For the unequally spaced volume-age data, the errors ($\boldsymbol{\varepsilon}_i$) are likely correlated and unequally varied. To assess this, a large number of error structures were examined, along with various error variance functions and weighting factors. The SP(pow) and SP(lin) structures illustrated in Eqs. (9) and (10) gave the most reasonable fits, and the error variances were found to increase monotonically with age and predicted volume. Hence, $\sigma_i^2=\sigma^2 x_{ij}^{\lambda}$ and $\sigma_i^2=\sigma^2 x_{ij}^{\lambda}\hat{y}_{ij}^{k}$ were evaluated. Different λ and k values starting from 0.05 with an increment of 0.05 were examined. The best λ and k that produced the best fits (i.e., with the smallest AICs and BICs) were identified. Results from the FO method are listed in Tables 1 and 2. Fitted curves and residual plots from the iid structure and SP(lin) structure with $W=Age_{ij}^{-1.25}$ are shown in Fig. 1. The FOCE method did not achieve convergence in all cases and was not explored further.

Based on the results in Table 1, one would choose SP(lin) with $W=Age_{ij}^{-1.25}$ to be the best structure, because it produced the smallest AIC and BIC values. The fit from the iid structure would be considered the worst because it had the largest AIC and BIC values.

To verify if accounting for the non-iid errors provided the best fit, the statistics defined in Eq. (21) were obtained directly as a part of model fitting (Table 1). The overall accuracy δ indicates that the fit from the iid structure is the best. This can be seen in Fig. 1, where the residuals from the iid are spread narrower than those from the "best" fit of SP(lin) with $W=Age_{ij}^{-1.25}$.

The validation data were used to verify if the above observation on the modeling data holds. Two types of prediction were done for this purpose, illustrated next based on the

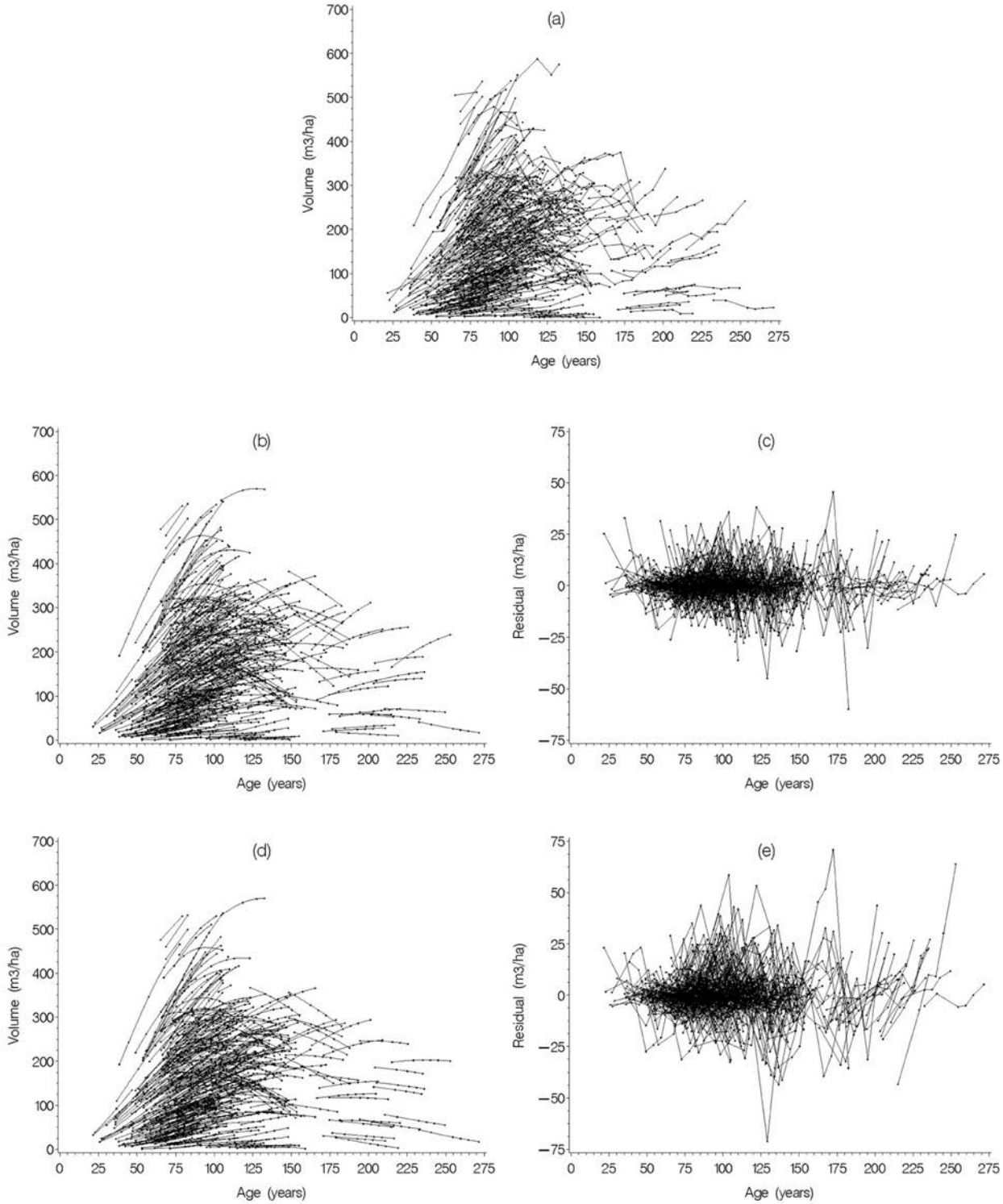

Fig. 1 White spruce volume-age modeling data (a), and fitted curves and residual trajectories for model (22) from the FO-iid structure (b, c) and FO-SP(lin) with $W = Age_{ij}^{-1.25}$ structure (d, e)

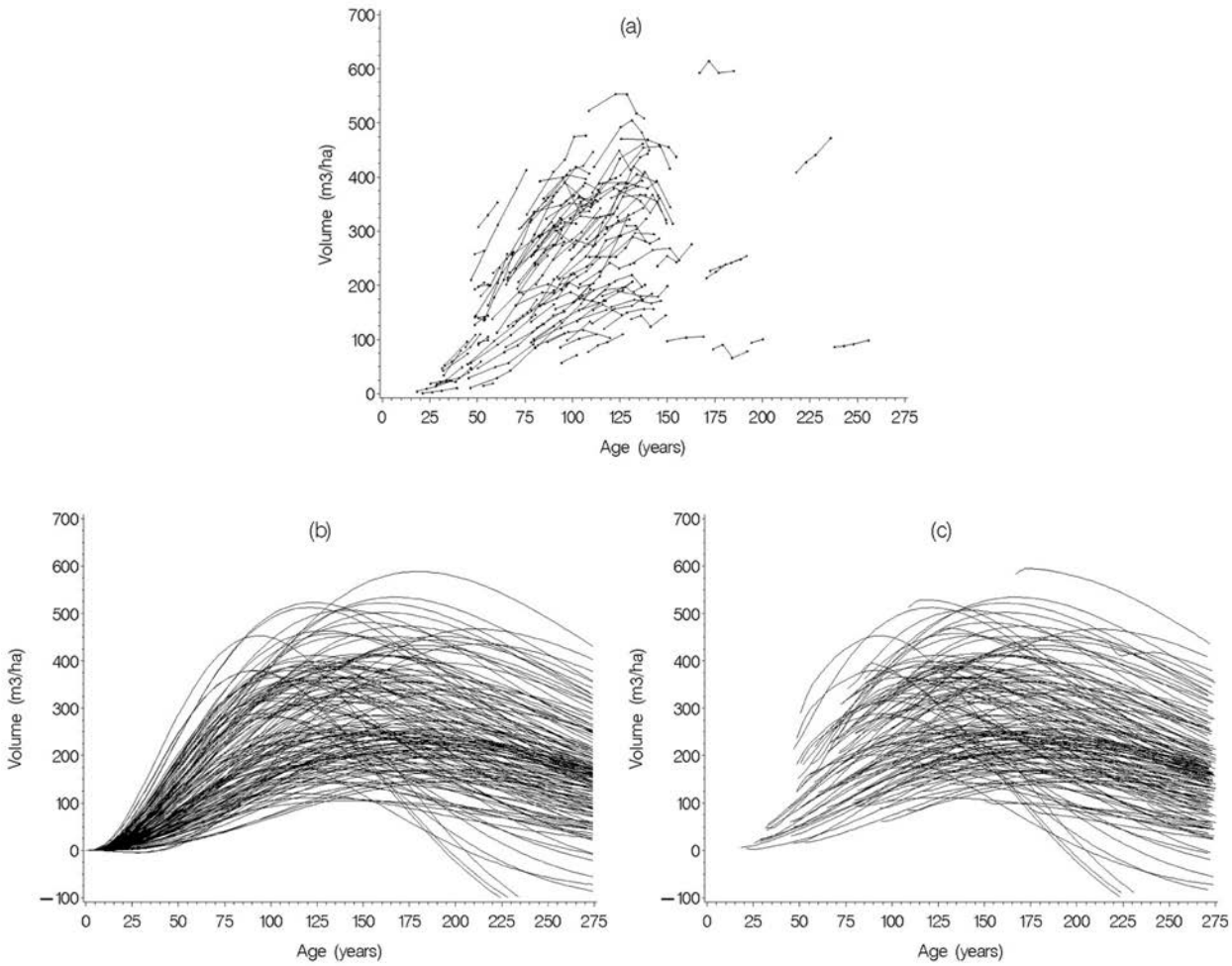

Fig. 2 White spruce volume-age validation data (a), and spaghetti plots of unadjusted (b) and adjusted (c) predictions from Type-1 prediction

For adjusted predictions, only future (forward) predictions beyond the initial observation of each plot were made.

Table 1 Fit statistics for model (22) from the first-order (FO) method on the modeling data

Type	Covariance structure	AIC	BIC	$\bar{e}$	$\lvert\bar{e}\rvert$	SD	δ
1	iid	19,025.4	19,050.2	0.0357	5.4971	8.1960	67.176
2	SP(pow)	18,786.5	18,815.5	0.0797	7.4461	10.7417	115.390
3	SP(pow), $W = Age_{ij}^{-1.35}$	18,658.3	18,687.3	−0.4865	13.4710	17.5678	308.864
4	SP(pow), $W = \hat{V}ol_{ij}^{-1.25}$	18,693.4	18,722.4	−1.5084	20.2942	25.6269	659.013
5	SP(pow), $W = Age_{ij}^{-1.0}\,\hat{Vol}_{ij}^{-0.4}$	18,657.6	18,686.6	−1.0078	16.8665	21.5238	464.290
6	SP(lin)	18,770.2	18,799.2	0.1714	7.0902	10.5107	110.504
7	SP(lin), $W = Age_{ij}^{-1.25}$	18,652.6	18,681.6	0.2300	7.0829	10.6361	113.180
8	SP(lin), $W = Age_{ij}^{-1.2}\,\hat{Vol}_{ij}^{-0.05}$	18,653.1	18,682.1	0.2213	7.0796	10.6273	112.988
9	TOEPH(3), $W = Age_{ij}^{-1.10}$	18,794.7	18,852.7	0.3789	6.3359	9.7749	95.692

Note: $\hat{Vol}_{ij}$ is predicted volume, AIC, BIC, $\bar{e}$, $\lvert\bar{e}\rvert$, SD and δ are defined in Eqs. (13) and (21). SP(pow), SP(lin), and TOEPH(3) are spatial power, spatial linear, and Toeplitz with three bands, respectively. The statistics were obtained from m = 465 subjects (plots) with N = 2013 total observations.

Table 2 Parameter estimates for model (22) based on selected error covariance structures and the first-order (FO) method

Parameter	Covariance structure type					
	1	2	5	6	7	8
β_1	0.01718	0.01728	0.01736	0.01735	0.01747	0.01746
β_2	2.3893	2.3916	2.3938	2.3919	2.3947	2.3946
$\sigma^2_{b_1}$	0.000091	0.000075	0.000065	0.000078	0.000077	0.000077
$\sigma_{b_1 b_2}$	0.001398	0.001199	0.001022	0.001263	0.001187	0.00119
$\sigma^2_{b_2}$	0.03712	0.03328	0.02762	0.03464	0.03248	0.03255
ρ		0.9717	0.9944	0.03817	0.03777	0.03776
σ^2	114.24	479.14	2.8419	321.96	0.9617	0.9378

Note: Covariance structure type refers to the "Type" defined in Table 1, β_1 and β_2 are fixed parameters, $\sigma^2_{b_1}$ and $\sigma^2_{b_2}$ are the variances for random parameters b_1 and b_2, respectively, $\sigma_{b_1 b_2}$ is the covariance between b_1 and b_2, ρ is the correlation parameter, and σ^2 is the error variance.

SP(lin) with $W = Age_{ij}^{-1.25}$ structure and a plot measured four times at 218, 223, 228 and 236 years, with respective volumes of 408.903, 427.104, 440.770 and 471.987 (m^3/ha).

For the first type of prediction, termed Type-1 prediction here, the random parameters $\hat{\boldsymbol{b}}_i$ were predicted using Eq. (4) based on all four observations of the plot. The derivatives of Eq. (22) with respect to b_1 and b_2 (der_b_1 and der_b_2), which constitute the $\boldsymbol{Z}_i$ matrix in Eq. (4), were obtained as:

$$der_b_1 = \boldsymbol{Age}_i^{\hat{\beta}_2}(1-\hat{\beta}_1\boldsymbol{Age}_i)\exp(-\hat{\beta}_1\boldsymbol{Age}_i)$$

$$der_b_2 = \hat{\beta}_1\exp(-\hat{\beta}_1\boldsymbol{Age}_i)\boldsymbol{Age}_i^{\hat{\beta}_2}\ln(\boldsymbol{Age}_i)$$

where $\hat{\beta}_1 = 0.01747$ and $\hat{\beta}_2 = 2.3947$ (from Table 2). The $\boldsymbol{R}_i$ for SP(lin) with $W = Age_{ij}^{-1.25}$ is:

$$\boldsymbol{R}_i = \sigma^2\begin{bmatrix} x_{i1}^{\lambda} & x_{i1}^{\lambda/2}x_{i2}^{\lambda/2}(1-\rho d_{12}) & x_{i1}^{\lambda/2}x_{i3}^{\lambda/2}(1-\rho d_{13}) & x_{i1}^{\lambda/2}x_{i4}^{\lambda/2}(1-\rho d_{14}) \\ & x_{i2}^{\lambda} & x_{i2}^{\lambda/2}x_{i3}^{\lambda/2}(1-\rho d_{23}) & x_{i2}^{\lambda/2}x_{i4}^{\lambda/2}(1-\rho d_{24}) \\ & & x_{i3}^{\lambda} & x_{i3}^{\lambda/2}x_{i4}^{\lambda/2}(1-\rho d_{34}) \\ & & & x_{i4}^{\lambda} \end{bmatrix} \tag{23}$$

where $\lambda = 1.25$, $x_{i1} = 218$, $x_{i2} = 223$, $x_{i3} = 228$, $x_{i4} = 236$, $d_{12} = (223-218) = 5$, $d_{13} = 10$, $d_{14} = 18$, $d_{23} = 5$, $d_{24} = 13$, $d_{34} = 8$, $\rho = 0.03777$, $\sigma^2 = 0.9617$, and $\sigma^2_{b_1} = 0.000077$, $\sigma^2_{b_2} = 0.03248$ and $\sigma_{b_1 b_2} = 0.001187$ for the $\hat{\boldsymbol{D}}$ matrix (from Table 2). Therefore,

$$\hat{\boldsymbol{b}}_i = \hat{\boldsymbol{D}}\boldsymbol{Z}_i'(\boldsymbol{Z}_i\hat{\boldsymbol{D}}\boldsymbol{Z}_i' + \hat{\boldsymbol{R}}_i)^{-1}(\boldsymbol{Vol}_i - \hat{\boldsymbol{Vol}}_{i_fix}) = [-0.01773, -0.19170]$$

where $\hat{\boldsymbol{Vol}}_{i_fix}$ are the predicted volumes from the fixed parameters only. Once the $\hat{\boldsymbol{b}}_i$ are known, the unadjusted predicted volumes from Eq. (14) are obtained as:

$$\hat{\boldsymbol{Vol}}_i = \hat{\boldsymbol{Vol}}_{i_fix} + \boldsymbol{Z}_i\hat{\boldsymbol{b}}_i = [434.653, 433.104, 430.692, 425.174].$$

The adjusted predicted volumes at future times are calculated based on the initial observation at 218 years, which has a residual of $e_1 = (Vol_1 - \hat{Vol}_1) = (408.903 - 434.653) = -25.75$. Thus, following Eq. (16), the adjusted predicted volumes at 223, 228, and 236 years can be calculated. For example:

$$\hat{Vol}_{236} = (\hat{Vol}_{236_fix} + \boldsymbol{Z}_{236}\hat{\boldsymbol{b}}_i) + Age_1^{1.25/2}Age_4^{1.25/2}(1-\rho d_{14})(Age_1^{1.25})^{-1}e_1 = 416.511.$$

Note that there is no adjustment for the initial observation. Therefore, the prediction statistics calculated for all plots (Table 3) excluded the initial observation of each plot.

For the second type of prediction, termed Type-2 prediction, only the initial observation from each plot was used to predict the $\hat{\boldsymbol{b}}_i$. For the example plot, the $\hat{\boldsymbol{b}}_i$ were found to be: $\hat{\boldsymbol{b}}_i = [-0.010856, -0.02889]$, with a residual $e_1 = 9.4704$. The unadjusted and adjusted volume predictions were done for the (4-1) future observations. All other computations are similar to those for Type-1 prediction. Results from all 135 validation plots are shown in Table 3 and Fig. 2.

Three distinct trends are observed from Table 3. First, for both prediction types, the δs from the iid structure are smaller than those from the generalized structures, suggesting a better accuracy of prediction from the iid structure. The same phenomenon was also observed on the modeling data (Table 1 and Fig. 1). Second, the adjusted predictions are not always better than the unadjusted ones. For instance, for SP(lin) with $W = Age_{ij}^{-1.25}$, the $\bar{e}$, $|\bar{e}|$, SD and δ statistics for the unadjusted predictions from Type-1 prediction are all smaller than their counterparts for the adjusted predictions. Third, the $\bar{e}$, $|\bar{e}|$, SD and δ statistics from Type-1 prediction are always smaller than their counterparts from Type-2 prediction, suggesting Type-1 prediction produced more accurate predictions than the corresponding Type-2 prediction. This last trend is expected and is consistent with those found in other studies (e.g., HUANG *et al.*,

Table 3 Prediction statistics for model (22) on the validation data

PT	Covariance structure		N	$\bar{e}$	$\lvert\bar{e}\rvert$	SD	δ
1	iid		351	1.1414	6.9642	9.3403	88.54
	SP(pow)	Unadj	351	4.0918	8.9711	11.8813	157.91
		Adj	351	5.7826	10.3702	13.0183	202.92
	SP(pow), $W=Age_{ij}^{-1.35}$	Unadj	351	14.0655	18.5044	20.9949	638.62
		Adj	351	8.9972	13.5613	15.6443	325.69
	SP(pow), $W=Age_{ij}^{-1.0}\hat{Vol}_{ij}^{-0.4}$	Unadj	351	17.8170	23.0175	24.8440	934.67
		Adj	351	9.5672	14.0652	15.9488	345.90
	SP(lin)	Unadj	351	3.6850	8.8409	12.2189	162.88
		Adj	351	4.9165	9.6374	12.6405	183.95
	SP(lin), $W=Age_{ij}^{-1.25}$	Unadj	351	4.2849	9.0012	12.3511	170.91
		Adj	351	5.4190	9.9800	12.8342	194.08
	SP(lin), $W=Age_{ij}^{-1.2}\hat{Vol}_{ij}^{-0.05}$	Unadj	351	4.2843	9.0023	12.3506	170.89
		Adj	351	5.4266	9.9848	12.8343	194.17
2	iid		351	20.2025	27.7361	30.7223	1,352.00
	SP(pow)	Unadj	351	22.0884	28.8040	31.2983	1,467.48
		Adj	351	20.7649	28.0925	30.9799	1,390.94
	SP(pow), $W=Age_{ij}^{-1.35}$	Unadj	351	27.8034	33.2810	34.4197	1,957.74
		Adj	351	20.3992	27.7908	30.7113	1,359.31
	SP(pow), $W=Age_{ij}^{-1.0}\hat{Vol}_{ij}^{-0.4}$	Unadj	351	30.8329	36.5177	36.6414	2,293.26
		Adj	351	20.5366	27.8078	30.6831	1,363.20
	SP(lin)	Unadj	351	21.8292	28.5801	31.1176	1,444.82
		Adj	351	21.4319	28.3758	31.0905	1,425.95
	SP(lin), $W=Age_{ij}^{-1.25}$	Unadj	351	21.6170	28.2494	30.7957	1,415.67
		Adj	351	21.2003	28.0782	30.7733	1,396.45
	SP(lin), $W=Age_{ij}^{-1.2}\hat{Vol}_{ij}^{-0.05}$	Unadj	351	21.6211	28.2355	30.7854	1,415.21
		Adj	351	21.2047	28.0692	30.7659	1,396.18

Note: PT is the prediction type defined in the main text, Unadj is unadjusted prediction (Eq. (14)), Adj is adjusted prediction (Eq. (16)), $\bar{e}$, $\lvert\bar{e}\rvert$, SD and δ are prediction statistics (Eq. (21)), and N is the difference between the number of measurements (486) and number of plots (135).

2009b). It is because the $\hat{\boldsymbol{b}}_i$ in Type-1 prediction were obtained based on all observations from each subject, whereas the $\hat{\boldsymbol{b}}_i$ in Type-2 prediction were obtained based on one initial observation only.

DISCUSSION

Much of the forest data collected from PSPs and sectioned trees are unequally spaced and unbalanced longitudinal data, which are often correlated and heteroscedastic. It is well known in theory that the consequences of ignoring correlated and heteroscedastic errors for ordinary least squares estimation could be serious. The standard errors of the estimated coefficients tend to be under-estimated, which could cause the usual t-scores to be over-estimated and the F-test to be unreliable. This could subsequently lead to the insignificant coefficients appear to be significant, producing invalid hypothesis testing and interval estimation about the model coefficients.

The correlated and heteroscedastic white spruce volume-age data from PSPs were used in this study to demonstrate model estimation and prediction under the NLMM framework. The results were compared to those obtained assuming the iid structure. To our surprise, they showed that the model fitted with the iid structure predicted consistently better than those fitted with non-iid structures. This was true on both model fitting and validation datasets. It suggested that, under the

NLMM framework, the simple iid structure achieved better prediction accuracies in all cases.

Between the predictions obtained with and without accounting for the non-iid structures, we compared the predictions from Eq. (14) that ignored the correction factor $\boldsymbol{V}'\boldsymbol{\Psi}^{-1}\dot{\boldsymbol{e}}$ to those that accounted for it from Eq. (16) (Table 3). For Type-1 prediction, the accuracy (δ) indicated no consistent pattern between unadjusted and adjusted predictions. For Type-2 prediction, the δs for unadjusted predictions were larger than their adjusted counterparts. But for both prediction types, the δs from the non-iid structures were always greater than those from the iid structure, suggesting lower accuracies from the non-iid structures regardless of adjusting or not.

There are several possible reasons that explain why the iid structure produced more accurate predictions than generalized structures. First, although the standard errors (SEs) of the estimated coefficients may be under-estimated if the presence of non-iid errors are unaccounted for, the coefficients themselves are still unbiased on original data under the iid assumption. But the unbiasedness of the coefficients from the estimation that accounted for the non-iid errors was derived from transformed data, which could make it inferior for predictions on untransformed data. Since the vast majority of forest models are developed to be used as prediction models on untransformed data once the model coefficients have been estimated, the consistency between model estimation and prediction is of the greatest importance when deciding the appropriateness of a fitted model. Failing to recognize this, a good model in theory may turn out to be a bad one in practice. For prediction models, the inferences on predictions (e.g., HAHN and MEEKER, 1991; GRAYBILL and IYER, 1994) are unrelated to the SEs of the estimated model coefficients.

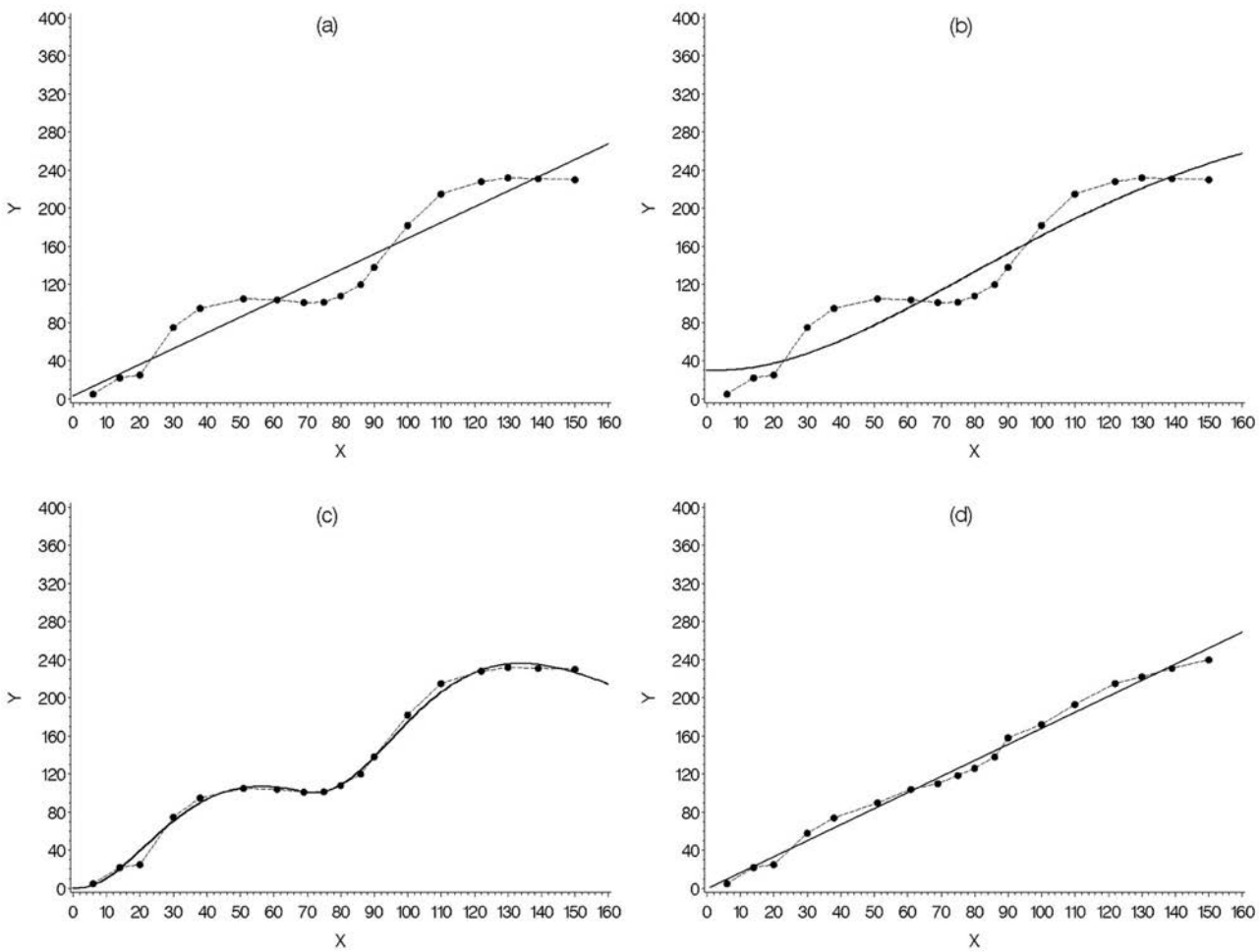

Fig. 3 An illustration of correlated data (●) fitted by an inadequate linear model (a), an inadequate nonlinear model (b), an adequate nonlinear model (c), and an adequate linear model (d)

Correlated errors are present in (a) and (b), but not in (c) and (d). Note that "correlated data" are different from "correlated errors". In a statistical sense correlated errors may not exist for correlated data if an adequate model is fit (as in (c)), or if the correlation is smaller than a critical threshold (as in (d)).

Second, the ineffectiveness of accounting for the non-iid structures in predictions is likely attributed to the NLMM technique itself, which already allows for the accounting of correlated and heteroscedastic errors through random parameters (JONES, 1990; DAVIDIAN and GILTINAN, 1995). This rendered any additional accounting of the non-iid errors unnecessary or unimportant. In fact, the additional accounting may result in over-fitting a NLMM.

Third, the better performance of the iid structure is probably related to the performance criteria used in Eq. (21), which usually favor the iid structure. This is because the mean prediction bias $\bar{e}$, the *SD* of the prediction errors, and the overall accuracy measure δ, are most consistent with the criteria for optimizing parameter estimates under the NLMM with iid structure, enabling the iid structure to show better performance than other structures. While other criteria could be used as well (e.g., HUANG *et al.*, 2009b), we believe that, prior to any new and better criteria are developed, those defined in Eq. (21) are still most relevant. One caveat about the criteria is that, the practice of using AIC and BIC as the key measures to select a preferred model or error structure in NLMM studies, may deserve further evaluation. Smaller AIC and BIC values, which were supposed to indicate a better model, were shown to produce worse predictions in this study.

The other reason that the iid is better in predictions is likely related to the magnitude of the correlation and heteroscedasticity, and the adequacy of the specified model in relation to the data. If there is a true strong correlation among error terms, as illustrated in Fig. 3 (a)-(b) where a poor model was fit for the correlated data that exhibit strong oscillation, it would be better to consider it for prediction purpose. However, if an adequate model is fit to remove the oscillation (e.g., Fig. 3 (c)), and/or the correlation is less than certain critical value after the fit (e.g., Fig. 3 (d)), there would be a case with good prediction without considering correlation. It is possible that the weak oscillation of the volume-age data, a reasonably specified nonlinear model, and the inclusion of the right random parameters in the model together removed the need to account for the correlation and heteroscedasticity in the data.

Lastly, the inferior prediction from accounting correlated errors could be caused by the error of the first observation, which impacts all future prediction errors. The prediction based on the iid structure, on the other hand, is independent of the error of the first observation. The first observation in a forest growth series usually occurs at a young age when the growth is unstable, leading to a large initial error that propagates to other errors over time.

In conclusion, our results showed that, under the NLMM framework, the model fitted with the iid structure performed better in predictions than that fitted with other more complex structures. This has important practical implications, as a better prediction model can be fitted with a simpler error structure. For our data there appears to be no real benefit to evoke more elaborate error structures. The NLMM technique itself is powerful enough to account for generalized error structures through random parameters. Within the NLMM context, if a proper model is specified, there is really no need to account for the non-iid errors other than for making inference on model coefficients, which is irrelevant to model prediction. Further research should be conducted to see if the results obtained in this study still hold for other types of models and data, especially independent data not used in model fitting. Additional studies on the use of AIC and BIC in determining the goodness-of-fit of NLMMs should also prove to be very useful.

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Article

Multi-scale Forest Inventory and Modelling for Multi-purpose Management

Cris Brack[*1,2], Chris McElhinny[*2], Robert Waterworth[*2] and Simon Roberts[*2]

ABSTRACT

Forests provide many goods and services and the demands for quality information about forests are continuing to increase. These demands include detailed information about an increasing range of forest characteristics and resources - both wood and non-wood based - on small, nominated units of land. For example, Kyoto-type carbon credit schemes operating at a high tier, and therefore in the most valuable markets, require precise and unbiased estimation of carbon pools in forests at specific sub-hectare locations. Simultaneously, landscape-level management decisions, especially those related to biodiversity, may require information about stand characteristics and their spatial distribution over thousands of ha or km^2. Historical approaches for forest inventory were often classified into strategic/national, operational/regional or tactical/local scales to support management decisions at corresponding scales. However, recent trends of increased attention to the role of even individual forests in local and global economies and environments – evidenced by international conventions and agreements like the Montreal Agreement or Kyoto Protocol, and international monitoring of specific areas of deforestation and degradation – has reduced the usefulness of the strategic/operational/tactical separation. Strategic decisions made during international policy negotiations may significantly affect tactical or on ground decisions on specific forested lands, while conversely good but independent tactical decisions may put strategic management goals at risk. Disagreement amongst inventories at the various levels (e.g. where the sum of tactical inventories does not equal the strategic inventory) increases the probability for conflict between strategic and tactical management decisions. This paper summarises the framework used in the National Carbon Accounting System (NCAS) developed by the Commonwealth Government of Australia to support policy-development especially in relation to global climate change and forests. The framework allows for the integration of information captured through long-term satellite sensing, physiological and empirical modelling, field-based measurements and regional "text" information. Although policy-development is obviously at a "strategic" level, the framework is flexible enough to also provide information at sub-hectare levels and supports seamless tactical decision-making as well. The information provided supports Commonwealth policy development and this paper demonstrates how NCAS also provides valuable information for other management purposes ranging from tactical management of fuelwood and farm timbers at the scale of individual farm forests, through to landscape-level structural diversity and biodiversity management.

Keywords: Carbon accounting, multi-scale inventory, forest management, forest biodiversity

Corresponding author: Cris Brack
E-mail: Cris.Brack@waiariki.ac.nz
[*1] School of Forestry and Primary Industries, Waiariki Institute of Technology, Private Bag 3028, Rotorua 3046, New Zealand
[*2] The Fenner School of Environment and Society, Australian National University, Canberra, ACT 0200, Australia

INTRODUCTION

Forest inventory and sampling textbooks have long concentrated on precise and unbiased estimation of the mean tree or hectare in a forest (e.g. COCHRAN, 1977). Simple random and systematic sampling approaches have been in existence for over a century, and were used to estimate population means for the extensive tracks of forest land opening up during the development of the USA and Australia. Long accepted theory and practice allows these methods to include predictions of sam-

pling error and therefore some certainty as to how close the estimated value is to the *true* population mean value. Many inventories are designed in terms of this sampling error around the mean. It was relatively unimportant that the yields in any one year or over any sub-set of the forest were not similar to the population mean because it was anticipated that once the whole of the land had been treated, the true mean would be within the sampling error bounds. The non-importance of the estimates for forest sub-sections however is no longer the case. Forest inventory questions may no longer relate to total population or even strata means, but rather need to relate to questions about specific, small areas of the forest.

The scale at which inventory data is relevant to decision makers has changed. NORTON *et al.* (1990) conclude that even national scale data may be used to resolve forest resource issues for areas as small as a 'few hectares', while RICHARDS and BRACK (2004a; b) note that sub-hectare spatial resolution may be necessary to meet international conventions such as those stemming from climate change negotiations and the Kyoto Protocol. LUND and IREMONGER (2000) state that nearly "all natural resource issues, whether they are environmental, social, economic, ecological or political, are national as well as global issues" and therefore continental scale information is essential to put even local and regional decisions in context. Thus, information collected during an inventory may have application for decision making over a wide range of scales.

The multi-scale issue was a dominant problem during the design of the National Carbon Accounting System (NCAS) for Australia. While specifically designed to provide for a robust national account of Australia's greenhouse gas emissions (i.e. national scale information), the system was also required to support location specific management and to deal with monitoring changes from pre-1990 land use change events (i.e. fine scale information) (BRACK *et al.*, 2006). An early finding in the development of NCAS was that national sample-based measurements of carbon stock or stock change at the scales necessary for location specific management or to deal with monitoring were not feasible (BRACK, 2007). In response, a model-based system was adopted where the biomass (and change) was predicted for each "analytical unit" (cell) across the country. Project, regional and national accounts can be determined by aggregating the appropriate cell estimates. These estimates are based on a hybrid model that integrates empirical and process modelling with remotely sensed data and information about historical and proposed land management. In addition to the estimation of mean or total greenhouse gas emissions over projects or regional scales, NCAS also provides fine spatial and temporal resolution and a framework for reporting a breadth of data (climate, soils, productivity, land cover and management information). This comprehensive data and modelling capability has not previously been available in a single system (BRACK *et al.*, 2006).

This paper outlines NCAS and provides examples of how the system has been integrated into forest inventory that supports forest management decisions at various scales.

NCAS DESCRIPTION

BRACK *et al.* (2006) provides a comprehensive description of NCAS. That paper also references some of the testing and model benchmarking for NCAS. There are essentially three major processes carried out for each analytical unit in the national coverage. The analytical units correspond to cells or pixels of about 625 m^2.

Identification of Woody Cover / Cover Change

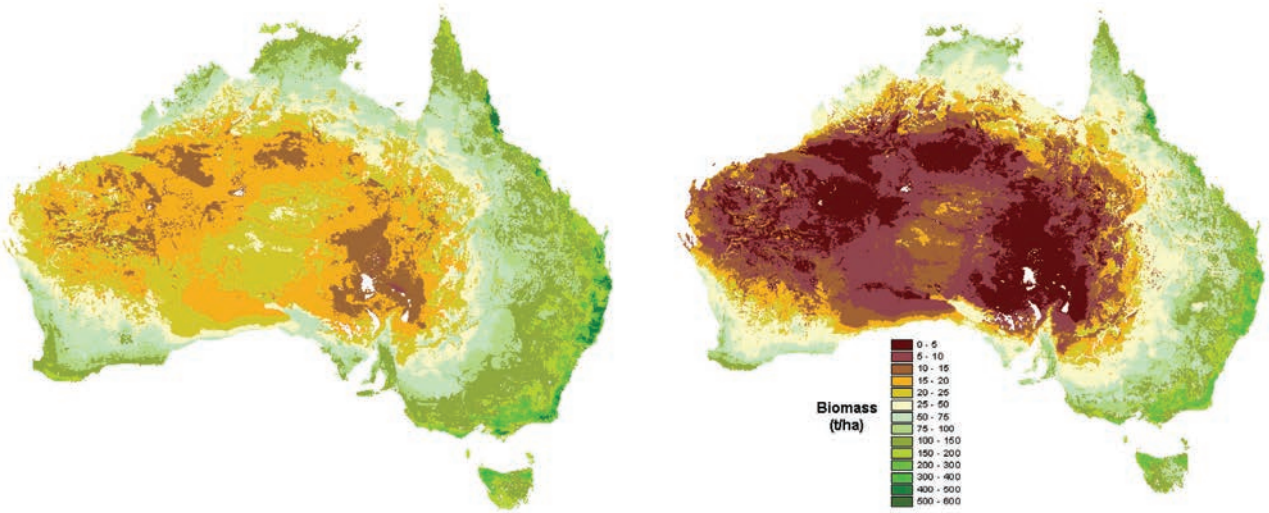
Each unit is identified as "woody" or "non-woody" and any change between these states (i.e. trees removed or established) identified. The changes are identified from, currently, 18 national coverages of Landsat satellite data (MSS, TM, and ETM+) from 1972 to 2008 (CACCETTA *et al.*, 2003). Conditional probability networks are used to combine the information provided by this suite of temporal coverages and reduce the likelihood of mis-classifying a genuine change in woody cover (KESTEVEN *et al.*, 2003). The detection of non-woody to woody change allows the identification of a "starting point" from which new trees can be assumed to begin growing, while detection of the reverse change identifies the point where decay from the various biomass pools due to harvest or disturbance begins.

Determination of the Forest Productivity Index (FPI)

The FPI is a continuous variable ranging from 0 - 25 that is related to the potential net primary productivity (NPP) of a nominal tree species growing at a site for which it is well adapted. It is derived from a simplified or truncated version of the 3-PG (Physiological Processes Predicting Growth) model of LANDSBERG and WARING (1997). In essence, the maximum NPP at any point is related to the photosynthetically active radiation (APAR) absorbed by plant canopies, but this maximum may be limited by soil fertility, available moisture or temperature extremes. The productivity index is calculated for each unit over each month using monthly climate surfaces and national coverages of soil moisture holding capacity and fertility (BRACK *et al.*, 2006):

$$\mathrm{FPI} = \mathrm{APAR} \times T \times S \times W \times 0.01 \times (1 - F)$$

where T denotes a variable between 0 and 1 that reduces the potential FPI if the monthly temperature deviates substantially from a range of temperatures; S denotes a level of fertility (high, medium and low); these levels depend on soil type, before environmental modifiers are applied; W denotes a variable between 0 and 1 which is calculated from the most limiting factor of soil water content or vapour pressure deficit; and F denotes the ratio of the number of frost days per month to the number of days in the month. A long term average of the



a) Long-term Net Primary Productivity Index (also termed the Forest Productivity Index)

b) Above ground biomass assuming long-term freedom from disturbance

Fig. 1 Examples of national coverages produced by NCAS

monthly estimates of FPI was also determined as a general index of productivity (Fig. 1a). The complete version of 3-PG would require detailed species specific information to apportion the NPP into the various within-tree pools, but NCAS does not implement this part of 3-PG.

Estimate Biomass

The long-term (undisturbed) above-ground biomass at each unit is calculated from a correlation quantified between FPI and field measurements of biomass on undisturbed sites (RICHARDS and BRACK, 2004a) (Fig. 1b).

Where a change in the wood / non-woody classification has been identified for the unit, NCAS assigns a probable management regime for the unit using a region-based database of likely activities (e.g. proportion of the time land clearing was associated with post-felling burning or ploughing etc). The year of the change and the assumed activities are used as input into models that estimate the biomass in various pools and how these pools change on an annual basis through growth (proportional to the monthly FPI) or decay (RICHARDS and BRACK, 2004b) (Fig. 2).

USING CONTINENTAL COVERAGE DATA

While NCAS has developed national coverages for the FPI and certain other layers, the identification of disturbance is not available over the entire nation. Instead, disturbance identification has been prioritised towards regions of land-use change that will influence the national accounts for carbon sequestration / emission and reporting under the Kyoto Protocols. Therefore coverages of disturbance on areas where there is no land-use change, e.g. harvesting on forest land which will remain as forest land, is not available. As a surrogate for this disturbance information, the following examples used measures of projected foliage cover (%) (PFC) derived from multiple satellite images or classifications of canopy structure derived from aerial photograph (API) determination. It was anticipated that, for a given FPI, a PFC close to 100% relates to forest stands with low and/or non-recent levels of disturbance, while PFC closer to 0% indicates heavy and recent disturbance. Similarly, eucalypt stands dominated by small and regular crowns indicates recovery from relatively recent disturbance, while stands dominated by large and irregular crowns indicates low levels of major disturbance.

BRACK (2007) claimed it is "...difficult to conceive of any parameter of national interest that is not at least weakly related to one or more of these available auxiliary variables..." where the auxiliary variables were related to disturbance and the productivity of the stand as modelled by NCAS. Any such correlation can be used to improve the precision of the mean or total estimate for the parameter of national or region interest (HAMILTON and BRACK, 1999; BRACK, 2004). Given the complete spatial coverage of the auxiliary variables, the correlations can also be used to provide management relevant information at the project or fine scale. The following examples (Fig. 3) demonstrate how the information on disturbance and productivity has been used for multi-scale information to support management at multiple scales for a range of goods and services.

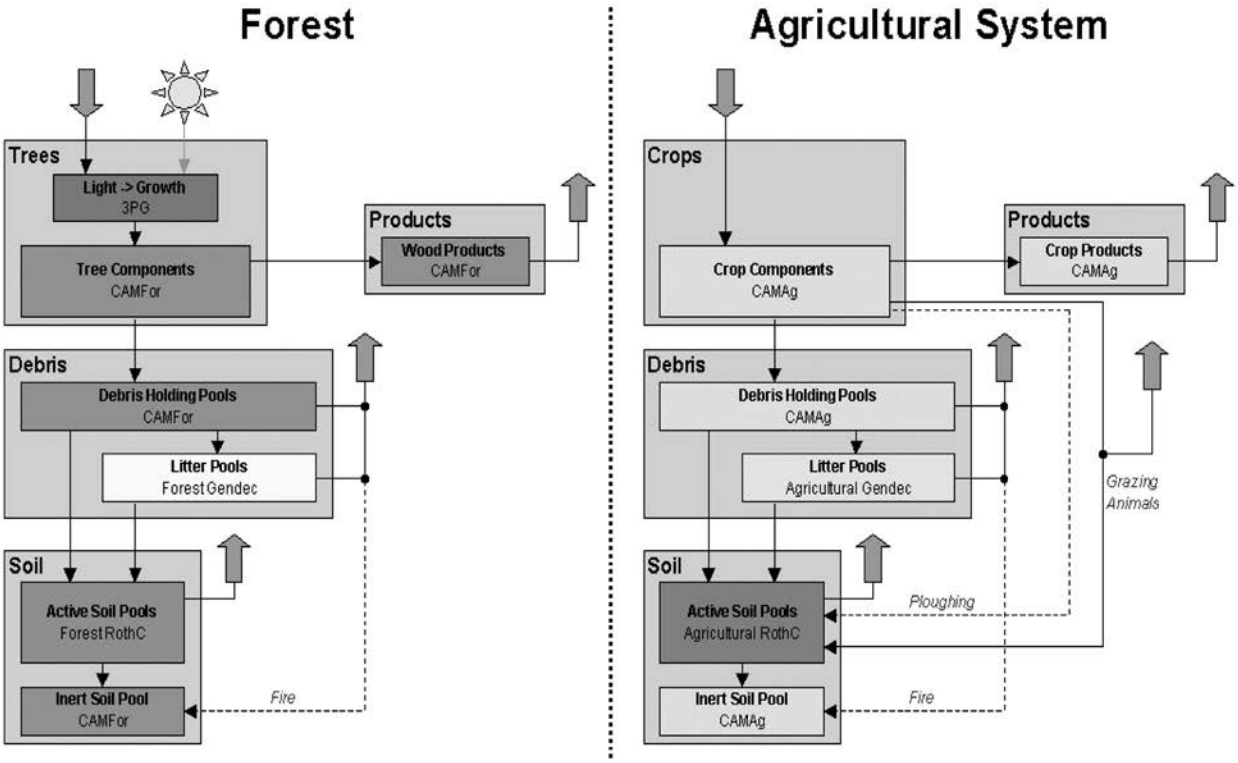


Fig. 2 Schematic of models used to estimate growth or transfer of carbon between pools in forests or agricultural lands (from RICHARDS and BRACK, 2004a)

Supporting Privately Managed Native Forests

Privately managed forest land (PMF) in the north east of NSW (Fig. 3, site 1) extends over 1.3 million ha and is gaining significance for their potential provision of commercial timber resources as well as their role in biodiversity. There was relatively little information about the PMF and the Bureau of Rural Sciences (BRS) of the Commonwealth Government commissioned an inventory to determine some basic resource data to assist in regional planning.

Previous experience in the privately managed forests of SE Queensland, immediately north of site 1 (Fig. 3), found that stratified random sampling, where strata were based on floristic or broad vegetation types was not effective in reducing sampling error. It was decided to use a multi-phase sampling approach with the long-term FPI data freely available from NCAS and FPC derived from a series of state-based remote sensing images as the auxiliary variables. The resolution of the FPC was 400 × 600 m, so the FPI for the analytical units were aggregated up into equivalent 400 × 600 m units, with the mean and variance estimated. Sixteen cluster plots were established across the range of FPI and FPC. Each cluster consisted of 25 angle-count sampling points (BAF=2). At three points within each cluster, fixed area plots were established where detailed tree measurements (including merchantable volume) and measurements related to structural diversity were collected. An

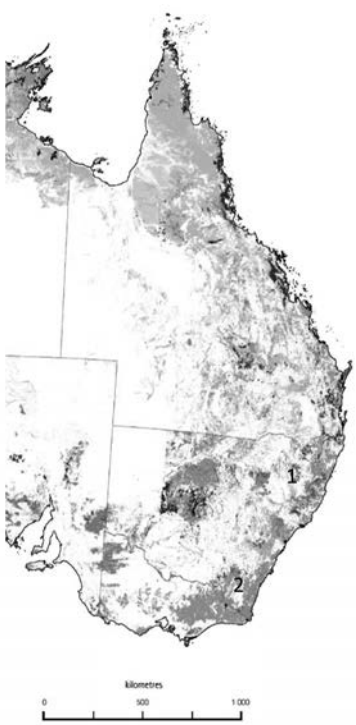


Fig. 3 Location of example study sites Numbers down the SE coast represent the example study areas discussed in this paper

Grey areas denote forested land along east coast of Australia.

additional 87 data points with merchantable volume (and precise location) collected previously were also made available.

The structural diversity measurements were related to a range of parameters identified by McElhinny *et al.* (2006) as being related to fauna species diversity in peer-review publications: Perennial species richness; Lifeform richness; Stand basal area; Quadratic mean DBH (cm); Vegetation cover <0.5 m (%); Vegetation cover 0.5–6 m (%); Number of regenerating stems; Number of hollow-bearing trees; Number of live stems ha^{-1} > 40 cm DBH; Number of dead trees ha^{-1}; Total log length (m); Total large log length (m); Litter dry weight (t ha^{-1}). The structural measurements allowed the creation of an index of stand structural diversity (McElhinny *et al.*, 2005) where low scores represented stands with most of the measured parameters towards the lower range observed in the measured population. The maximum structural diversity index (25) could theoretically only be obtained if every measurement in the cluster were in the upper quartile of the observed distributions, and would represent a stand with a structural diversity that is very attractive to a wide range of fauna.

Multiple linear regressions were fitted with FPI (mean and variance of the analytical units) and PFC, including interaction terms, as the independent variables. The variance of the FPI analytical units was not significant in any model. Significant models ($p<0.01$) with no observable deviations from normal and homogeneous distributions for the error, were fitted for cluster total volume, merchantable volume (Fig. 4a) and structural diversity index (Fig. 4b).

Estimates of the mean merchantable volume or structural index (and associated sampling error) can be made for the whole 1.3 million ha or any sub-regional by entering the corresponding mean FPI and PFC into the fitted linear models. The mean estimates for the sub-regions remain compatible with the overall regional values because of the structure of the linear model and because the FPI and PFC values are known for every individual unit in the region.

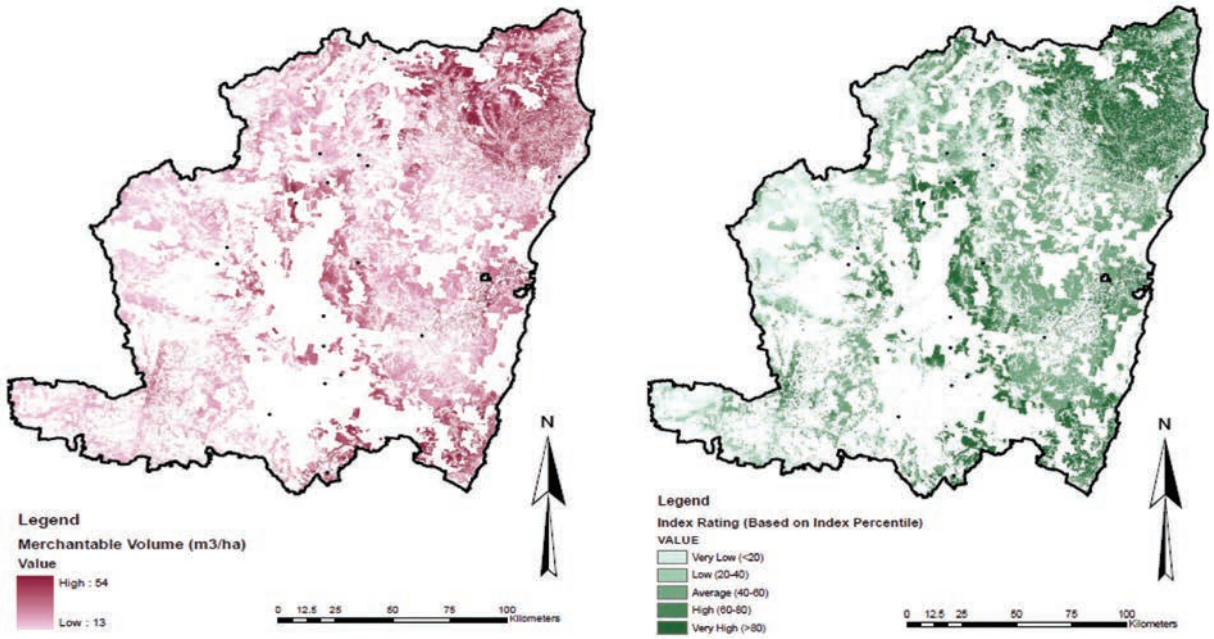
Individual land managers or Regional groups can use these maps to target areas of high biodiversity for protection or even low biodiversity for enhancement, as well as locating areas where commercial volumes of merchantable timber are available. They can also start to make meaningful trade-off calculations between the area they would need to harvest to generate minimum volumes of merchantable timber against relative changes in the structural biodiversity index. Such management analyses would not be possible if only mean values across the entire Region were the sole output from the inventory.

Farm Scale Volume Estimation

Southern Tablelands region in NSW covers approximately 150 × 300 km and includes a vast amount of dry sclerophyll forest (DSF) (Fig. 3, Site 2). The majority of these forests exist in a degraded state and could easily be improved in value, both ecologically and economically, through some form of silvicultural intervention. Significant areas of DSF are included in farms and rural blocks where landholders have a range of rationales for owning their private native forests. Most small land holders, for example, attribute the most important uses of native forests were enjoying its aesthetical and environmental benefits, while those with larger areas were likely to value their native forests for utilitarian purposes such as strategic grazing and timber production for on-property use (including firewood) and commercial timber production (May, 2006). However, there is concern that these private landholders do not utilise their DSF resources in an efficient or effective way (State Catchment Management Co-ordinating Committee, 2003). This under-utilisation is due to the individual landholders having a poor or incomplete knowledge of their own resources and the processing sector also unable to determine a well established and accepted method of quantifying timber available over the region from private property growers.

This project used FPI coverages available from NCAS and local knowledge about disturbance history. Historical information, including remotely sensed information, was relatively scarce in this area, so local farm owners were simply required to divide stands into two relative classes – regrowth after disturbance (stumps or other evidence of major disturbance present) and no recent disturbance. The objective was to provide farm-scale estimates of total volume of trees and the potential size of commercial activities, and the involvement of the farm manager was considered most appropriate for the disturbance classification. Again, it was important that these farm-scale estimates could be aggregated to different potential supply zones to support processing sector planning.

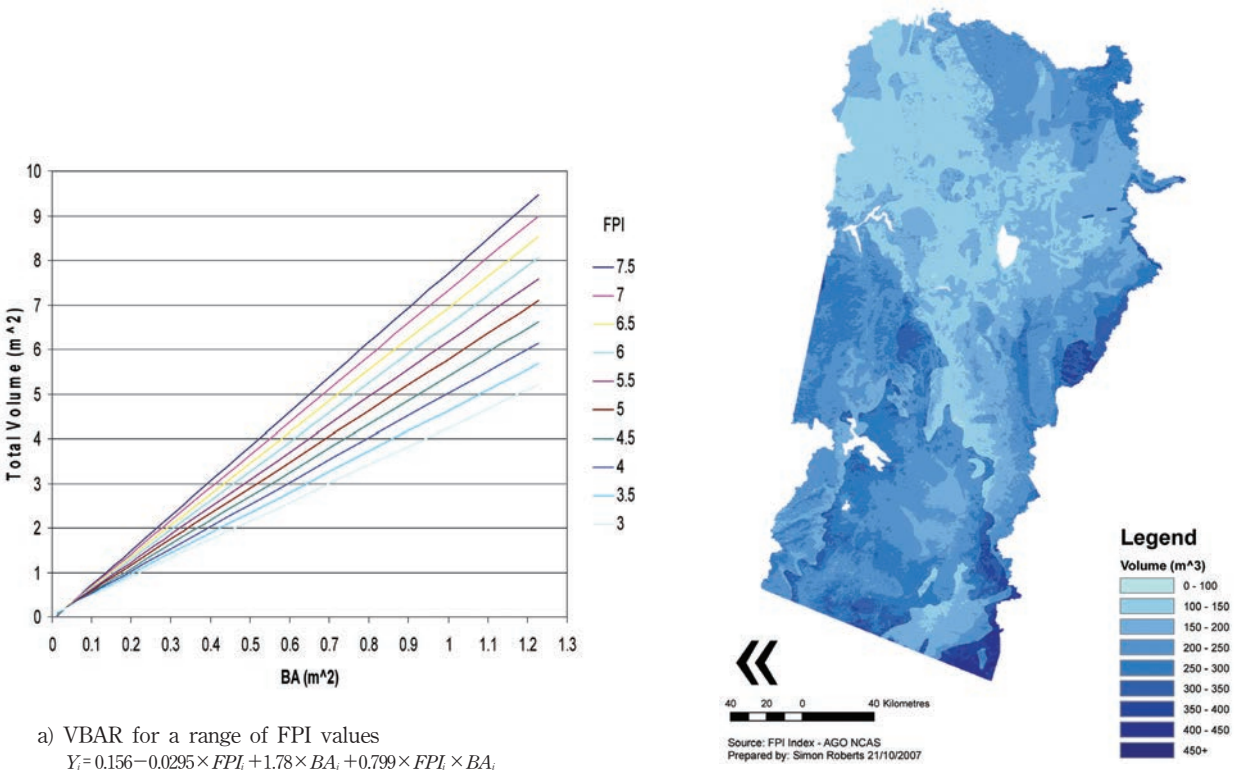
The first stage in developing farm-scale timber volume information was the development of a stand volume function that could be used by farmers who had no forest mensuration training. Using intensively measured tree volume data from sites that covered the range of FPI, a VBAR (Volume to Basal Area Ratio) approach was developed where the slope of the VBAR was correlated to the FPI (R^2 = 0.98) (Fig. 5a). Once reliable VBAR values were available and localised by FPI at a target location, the total volume was estimated for a large number of sites across the Southern Tablelands Region where stand basal area was known. These data were used to develop a correlation between FPI, disturbance and total volume (R^2= 0.61), which could then be used to produce a map of volume for the Region (Fig. 5b). A logistic regression was also fitted to estimate the number of trees that contained a solid-wood timber product as a function of FPI and disturbance (R^2 = 0.91). Farmers were encouraged to use the map and number of product trees to determine if the DSF on their farm was likely to support commercial activities (e.g. number of likely commercial trees exceeded a minimum level, with the minimum level set by the distance to access points). If there were a significant likelihood of a commercial activity, those farms could use the VBAR (Fig. 5a) and some simple angle-count inventory methods to confirm the availability of commercial quanti-



a) Merchantable volume (m^3 ha^{-1}) ; a regression against FPC, FPI and FPI^2
$R^2 = 0.59$; $n = 16$; $p < 0.0028$

b) Stand structural diversity; a regression against FPI and FPI^2
$R^2 = 0.49$; $n = 16$; $p < 0.0054$

Fig. 4 Maps of predictions based on multiple linear regressions using FPI and PFC



a) VBAR for a range of FPI values
$Y_i = 0.156 - 0.0295 \times FPI_i + 1.78 \times BA_i + 0.799 \times FPI_i \times BA_i$
$R^2 = 0.98$; RMSE = 0.0836; $n = 46$; $p < 0.0001$

b) Total volume (m^3 ha^{-1}) predicted by regression based on FPI and disturbance

Fig. 5 Stand-level estimates of volume for individual points across the Southern Tableland DSF

ties of timber.

As in the first example, estimates of the mean volume or number of solid-product trees (and associated sampling error) can be made for the whole Southern Tablelands or any sub-regional by entering the corresponding mean FPI and disturbance classifications into the fitted models. The mean estimates for the sub-regions remain compatible with the overall regional values because of the structure of the linear model and because the input values are known for every individual unit in the region.

CONCLUSIONS

Multiple coverages by satellites, long-term monthly climate surfaces and broad scale soil fertility maps have been brought together to create indices of forest growth at fine scale – both spatial and temporal. The fine-scale site quality index – FPI – integrates a wide range of physiological characteristics related to growth over the entire continent and has been made freely available. When combined with some measure of disturbance, FPI can be integrated into multi-phase sampling designs to produce estimates of volume (total and commercial) and biodiversity for specific locations which can be aggregated for reporting at a wide range of scales. The multi-phase sampling examples provided that use FPI and disturbance allow much more precise estimates of total values than those of stratified random sampling. The multi-phased approach also allows for estimates at specific spatial locations, which are superior to the stratified random sampling equivalent of assuming all points in a stratum are assigned the stratum mean value.

Further work may enhance the power of incorporating the fine temporal and spatial data that is increasing available through national projects like NCAS.

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Article

Adaptive Cluster Sampling in Inventorying Forest Damage by the Common Pine Sawfly (*Diprion pini*)

Mervi Talvitie*, Tuula Kantola*, Markus Holopainen* and Päivi Lyytikäinen-Saarenmaa*

ABSTRACT

Climate change and biological invasions are threats to healthy forest environments throughout the world. Some species that have previously caused only small-scale damage have now become serious pests, causing massive outbreaks and yield losses including in Scandinavia. The spatial scale of outbreaks and intensity of defoliation caused by the common pine sawfly (*Diprion pini* L.) can vary between years, due to fluctuation in population dynamics. The study area is situated in Ilomantsi, eastern Finland, where *D. pini* has caused vast needle losses in managed Scots pine stands. We aimed at developing an accurate and cost-efficient inventory method for insect damage, in which we compared stratified adaptive cluster sampling, random adaptive cluster sampling and simple random sampling. Stratified adaptive cluster sampling proved to be the most accurate method and was a promising candidate for inventorying and monitoring pest insect damage in the study. Adaptive cluster sampling is a promising method for inventorying and monitoring such phenomena when area does not remain constant all the time.

Keywords: adaptive cluster sampling, insect outbreak, defoliation, *Diprion pini*

INTRODUCTION

Climate change has caused rising temperatures throughout the world. Ecological balance has been interrupted, causing among other things pest damage in managed forests (Dale *et al.*, 2001; Evans *et al.*, 2002). The speed of change is higher at higher latitudes, as in Scandinavia. Forest insects, formerly regarded as harmless organisms during recent decades, are now causing serious damage in Finland (Lyytikäinen-Saarenmaa and Tomppo, 2002; de Somviele *et al.*, 2007). Economic losses can be considerable, appr. 300 - 1000 eur ha^{-1}, depending on intensity of needle loss. It can require over a decade for a tree to recover fully (Lyytikäinen-Saarenmaa *et al.*, 2006).

The common pine sawfly (*Diprion pini* L.) (Hymenoptera, Diprionidae) is a univoltine species in Scandinavia. The gregarious larvae actively consume all the needle age-classes of Scots pine (*Pinus sylvestris* L.) during August and September, which could lead to total defoliation of host trees in the climax phase of population dynamics (Viitasaari and Varama, 1987; Geri, 1988). Mature and maturing trees have the highest defoliation risk, but at peak densities seedlings can also suffer from defoliation (Geri, 1988; de Somviele *et al.*, 2004). *Diprion pini* hibernates in the cocoon stage and adult insects emerge early in the season. Diapause is typical for this species, lasting up to several years and prolonging outbreaks. Outbreaks have usually covered only some hundreds or thousands of hectares during the last 150 years, according to published records (e.g. Kangas, 1963; de Somviele *et al.*, 2007). A massive outbreak by *D. pini* occurred on dry and dryish pine forests in central Finland between 1997 and 2001, covering 500,000 ha (Lyytikäinen-Saarenmaa and Tomppo, 2002). The outbreak reached thus Ilomantsi district (eastern Finland) in 1999, where sawfly densities have fluctuated since then, showing a chronic nature.

Monitoring of sawfly outbreaks and defoliation is typically based on field sampling, i.e. collecting different life stages and performing analyses of this material in a laboratory (e.g. Juutinen and Varama, 1986). This kind of monitoring consumes extensive amounts of resources, and results may be biased. The method is still in use at the Finnish Forest Research Institute (Metla). The latest innovation in monitoring is based on semiochemicals, i.e. sex pheromones of sawflies, but

Corresponding author: Mervi Talvitie
E-mail: mervi. talvitie@helsinki. fi
* Department of Forest Science, University of Helsinki, P.O. Box 27, 00014 University of Helsinki, Finland

the method results in population and risk estimates only at the stand level (LYYTIKÄINEN-SAARENMAA *et al.*, 1999; 2006). Furthermore, estimates for forthcoming defoliation and yield losses may be indicative. Metla carries out the National Forest Inventory (NFI) every 10 years, when information on forest health as a side product of permanent and temporary field clusters is also collected at the coarse level (TOMPPO *et al.*, 2006). The NFI applies satellite data, e.g. Landsat Thematic Mapper (TM) images, but not for monitoring of forest disturbances. Long inventory periods and sparse layout of clusters result in problems for annual needs of precise information on forest disturbances and risk estimates for the coming years.

Deciding on an optimal inventory method is often the crucial phase for a certain research problem. The natural distribution of ecosystems is fragmented, mainly due to human intervention. Ecological distributions are very rarely randomly distributed (LEVIN, 1992). With conventional forest inventory methods, large areas must be covered to achieve acceptable precision of rare objects (GREEN, 1993; GREEN and YOUNG, 1993). Estimates need to be reliable; imprecise estimates may skew the real situation in the population and result in bad forest management decisions. Thus, prior information on the population of interest is crucial to decision-making (KANGAS and MALTAMO, 2006).

Adaptive cluster sampling (ACS) was suggested as a method for estimating rare and clustered populations that are difficult to estimate with high accuracy, using conventional sampling methods (THOMPSON, 1990; 1991; ROESCH, 1993; MAGNUSSEN *et al.*, 2005). Many studies concerning ACS have been undertaken with simulated data (e.g ROESCH, 1993; BROWN and MANLY, 1998; BROWN, 2003; SU and QUINN, 2003; MAGNUSSEN *et al.*, 2005). Few ACS studies, to our knowledge, have been done with actual data. ACHARYA *et al.* (2000) examined the density of three different rare tree species in Nepal with ACS, and TALVITIE *et al.* (2006) used ACS in inventorying coarse woody debris in the city forests of Helsinki.

The aim of the present study was to develop an accurate and cost-efficient inventory method for defoliating forest insects. ACS was chosen as the field inventory method. The defoliation estimate and variance of stratified ACS (ACS_{ST}) were compared with those of random ACS (ACS_{SRS}) and simple random sampling (SRS) inventories. ACS_{ST}, ACS_{SRS} and SRS samples were all based on the same field inventory and sample plots.

SAMPLING THEORY AND DESIGN

In sampling rare clustered phenomena, ACS has the advantage over other, more conventional sampling methods (e.g. THOMPSON, 1990; ROESCH, 1993). The initial set of units is selected, using a probability sampling procedure, and additional units are added to the sample from the neighbourhood of unit i in case the variable of interest (y_i) satisfies a given criterion, i.e. if $y_i \in C$, $C=\{x : x \geq c\}$. prior to sampling. The procedure is repeated until no new additional plots can be found whose variable exceeds the given value. Thus, sampling effort is focused on limited areas with a high number of interesting variables.

The population consists of N units $\{1, 2, \cdots, N\}$ and has variables of interest $y=\{y_1, y_2, \cdots, y_N\}$. In forest applications, a tree or sample plot is normally taken as a basic unit. For every unit i in the population, a physical neighbourhood A_i will be defined that consists of a collection of units that includes unit i. If unit j is in the neighbourhood of unit i, then unit i is also in the neighbourhood of unit j (THOMPSON, 1990).

A *network* is defined as a group of units whose values are all at least as large as the critical value C. A unit that does not satisfy this condition, but is in the neighbourhood of the unit that does, is referred to as an *edge unit* (THOMPSON, 1990). A network within its edge units is called a cluster. The difference from conventional sampling designs is that the procedure for selecting an adaptive sample is dependent on the population values observed in the field. The efficiency of the ACS method is dependent on the density and clustering degree, neither of which is known before the initial sampling. All the above-mentioned factors increase the uncertainty in choosing which study method to use in an investigation.

THOMPSON (1990) presented a modified HORWITZ-THOMPSON

Table 1 Simple random sampling and adaptive cluster sampling estimators and variances applied in the study

Estimator	Mean	Variance
Simple random sampling (SRS)	$\hat{\mu}_{SRS}=\frac{1}{n}\sum_{i=1}^{n} y_i$	$\mathrm{var}(\hat{\mu}_{SRS})=\frac{\sum_{i=1}^{n}(y_i-\hat{\mu}_{SRS})^2}{n-1}$
Adaptive cluster sampling (ACS)	$\hat{\mu}_{ACS}=\frac{1}{N}\sum_{k=1}^{K}\frac{y_k^*}{\alpha_k}$	$\hat{\mathrm{var}}(\hat{\mu}_{ACS})=\frac{1}{N^2}\left[\sum_{j=1}^{K}\sum_{k=1}^{K}\frac{y_j^* y_k^*}{\alpha_{jk}}\left(\frac{\alpha_{jk}}{\alpha_j\alpha_k}-1\right)\right]$

N=number of units in the population, n=number of units in the initial sample, K=number of distinct networks represented in the initial sample, y_i=observation in unit i, y^*_k=sum of observations in network k, α_k=the probability that the initial sample intersect network A_k, α_{jk}=the probability that the initial sample includes at least one unit in each of networks j and k.

(HT)-type (HORVITZ and THOMPSON, 1952) estimator designed for unbiased use in the ACS method. The HT estimator is based on the inclusion probabilities obtained from the data (THOMPSON, 1991). The HT estimator is rather indifferent to population structure (FELIX-MEDINA, 2003) and, therefore, encourages ecologists to use it in calculations (SALEHI, 2003).

The probability (α_k) that the initial sample intersects network A_k is defined as

$$\alpha_k = 1 - \binom{N - m_k}{n_1} \Big/ \binom{N}{n_1}, \quad (1)$$

where n_1 = initial sample size and m_k = the number of units in the network that includes unit k. The probability (α_{jk}) that the initial sample includes at least one unit in each of the networks j and k is defined in Eq. (2).

$$\alpha_{jk} = 1 - \left[\binom{N - m_j}{n_1} + \binom{N - m_k}{n_1} - \binom{N - m_j - m_k}{n_1}\right] \Big/ \binom{N}{n_1}, \quad (2)$$

where m_j is the number of units in the network that includes unit j. In comparison, the mean value of the SRS estimator is dependent only on the units in the initial sample and does not take into account units added in the second phase.

Stratified sampling is more effective than random or systematic sampling if the study area is not homogenous and the sampling effort is appropriately allocated (SHIVER and BORDERS, 1996). Moreover, stratified sampling with smaller sample size produces an estimate as precise as that obtained in nonstratified sampling, i.e. the same precision can be achieved at lower cost (SHIVER and BORDERS, 1996). First, the population is divided into rather homogenous subpopulations (strata) according to a certain variable, after which sampling is performed in each stratum separately. THOMPSON (1991) showed that an ACS_{ST} strategy is more accurate than the conventional ACS_{SRS} strategy in spatially clustered populations.

SAMPLING AND MEASUREMENT IN THE FIELD

The study area, Palokangas (62°52' N, 30°56' E), comprises 3,450 ha in the Ilomantsi district, eastern Finland (Fig. 1). The inventory was taken during May and June 2009, before elongation of current shoots. Since *D. pini* larvae cause defoliation in late summer, field measurements and defoliation assessment early in the season represent the defoliation intensity of the previous autumn. The forests in the study area are mainly pure pine stands on dry to dryish soil sites. Young or middle-aged stands are the majority (Table 2); the average age and diameter of the stands in the study area are 53 years and 14.7cm, respectively.

Diprion pini has caused severe defoliation and tree mortality since 1999 in the study area. The common assumption is that the species prefers only mature or maturing Scots pine trees (GERI, 1988; DAJOZ, 2000) and pine stands on shallow, infertile and well-drained soils (LARSSON and TENOW, 1984; VIITASAARI and VARAMA, 1987; MCMILLIN and WAGNER, 1993). In contrast to the results from previous studies in other countries, elevated defoliation has also been found in younger stands in the eastern parts of Finland, without clear evidence for a preference for only well-drained mineral soils (DE SOMVIELE *et al.*, 2004).

Table 2 Stand characteristics of the Palokangas study area

Variable	Average	s.d.
D (cm)	14.7	11.5
H (m)	11.6	8.7
V (m^3 ha^{-1})	72.8	71.1
Age (yrs)	53	37
Basal area (m^2 ha^{-1})	13.5	7.7
Trees ha^{-1}	1,394	1,336

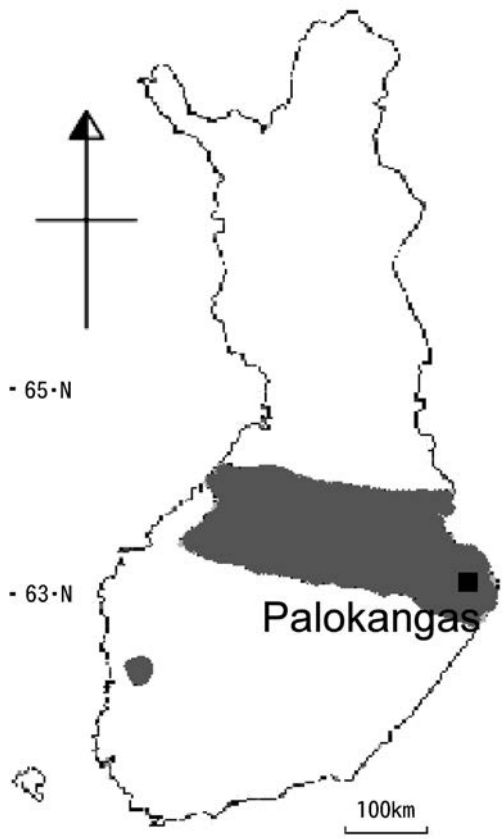

Fig. 1 Location of Palokangas study area. Areas infected by *D. pini* are seen as grey

The sample plots were situated 50 m from each other in the north-south and east-west directions. The position of each plot was obtained with a Trimble GPS Pathfinder Pro XH (Trimble Navigation Ltd., Sunnyvale, CA, USA), which can reach up to 30-cm accuracy. The locations were postprocessed with local base station data, resulting in an average error of app. 1-1.5 m. If a sample plot fell on the border of two stands, it was transferred towards a stand it more belonged to, thus avoi-

ding edge effects. All trees, having a diameter over 5 cm at breast height (1.3 m) were measured, using relascope sample plots (factor $q = 1$). For each tree in a sample plot, the species, diameter at breast height, distance and degree from the plot centre were measured. For pines, the defoliation percentage and canopy strata were determined. Every seventh tree of each species was taken as a sample tree. The height of the median trees for each sample plot and the sample trees were determined. Moreover, the age of the stand in a sample plot was determined from the median tree.

The inventory methods used were SRS, ACS_{ST} and ACS_{SRS}. All three methods were based on the initial or total sample plots: SRS only initial sample plots, ACS_{SRS} total sample size without stratification and ACS_{ST} total sample size with stratification. Stratification was performed according to site class and soil type, using the information on compartmentwise inventory, consisting of three strata: 1) high-productivity (HP) class, 2) low-productivity (LP) class, and 3) peatland (Table 3). The HP class contained dryish mineral soil site and sites more fertile than it, and the LP class contained sites poorer than the dryish mineral soil site. The third stratum included peatland plots. Within each stratum, sample plots were chosen, using SRS. There were a total of 55 initial sample plots taken in the sample, representing 0.5% of the total population.

The variable defoliation intensity of a sample plot was taken as the critical variable. Defoliation intensity was an indicator of the former *D. pini* outbreak intensity. The intensity of defoliation of a tree was visually estimated from different directions according to EICHHORN (1998), comparing the tree under investigation to a reference tree with full healthy foliage in the same site type; an accuracy of 10% was used. The defoliation intensity of a sample plot was calculated as the mean value of the defoliation intensity of each tree in the dominant and intermediate crown layers. The underlying trees were omitted from calculation of the plot mean due their limited ability to compete, which could skew the total plot defoliation. The critical value C was 20% in the present study; if the mean defoliation intensity in a sample plot was 20% or more, four additional sample plots were measured north, south, west and east of the unit. The defoliation intensity of 20% can be seen as a threshold value. Intensities less than 20% cause no serious harm to tree increment or mortality; however, a 20% intensity may decrease radial growth by 40–50% after needle consumption by *D. pini* (LYYTIKÄINEN-SAARENMAA *et al.*, 2006).

Table 3 Stratification in numbers within each stratum. Number (n) and percentages (%) of initial plots in the stratum

Stratum	n	%
HL	29	52.7
LP	20	36.4
peatland	6	10.9
total	*55*	*100*

RESULTS

The initial sample consisted of 55 and the total sample of 180 plots. Four additional units were on a road, and two sample plots were impossible to measure due to such narrow stands. There were three clusters in the HP stratum and three clusters in the LP stratum with at least one sample plot having a defoliation intensity over 20% (Table 4). No defoliation rate over 20% was found in the peatland class. The largest cluster, a total of 43 units, was found in HP (Fig. 2). The ACS meth-

Table 4 Clusters in the final sample, number of plots and their defoliation intensity in comparison to the critical value C=20%

Stratum	Cluster	Plots	$C \geq 20\%$	$C < 20\%$
HP	1	5	1	4
HP	2	43	20	23
HP	3	21	7	14
LP	4	21	7	14
LP	5	37	14	23
LP	6	5	1	4

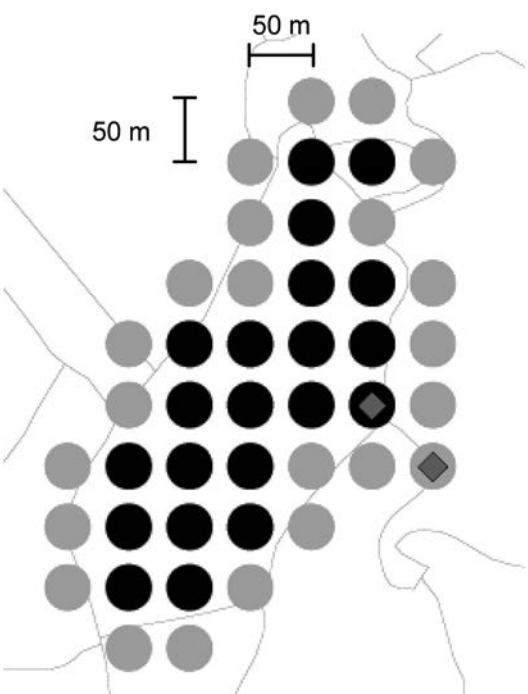

Fig. 2 Arrangement of a cluster. Initial sample plots (dark grey diamond), additional neighbouring plots satisfying the condition $C \geq 20\%$ (black circle) and additional plots, called edge units, with less than 20% defoliation (light grey circle)

Table 5 Number of units in the initial sample (n) and final sample (m), estimates (μ), variances (s^2) and coefficients of variation (CV) in each stratum and in the total population

Method	Stratum	n	m	μ	s^2	CV%
ACS_{ST}	total	55	180	8.3	21.4	55.7
	HP	*29*	*95*	*6.4*	*20.1*	*69.6*
	LP	*20*	*79*	*9.2*	*26.4*	*55.8*
	Peatland	*6*	*6*	*11.4*	*15.6*	*34.6*
ACS_{SRS}	total	55	180	8.3	30.1	66.2
SRS	total	55	55	8.5	109.3	123.2

ods were calculated, using the total sample plots (180 plots), while the SRS calculations were based on the initial sample plots.

The SRS, ACS_{ST} and ACS_{SRS} estimators for the defoliation mean and variance were calculated (Table 5). The mean values for all the estimators were very similar: 8.3% using ACS_{ST} and ACS_{SRS} to 8.5% using SRS. The mean value represents the mean defoliation index of the total study area. Within ACS_{ST} strata, the mean values varied between 6.4% in the richest HP soil class and 11.4% in peatland.

The coefficient of variation (CV) describes how much the variation is in relation to the estimate. It is a normalized measure of dispersion of a probability distribution and, thus, offers a way to compare the means and variances of different scales. The CV values are represented as percentages (Table 5). The smallest percentage for CV was found in ACS_{ST} (55.7%). Again, that of SRS (123.2%) was significantly larger.

DISCUSSION

In inventorying rare and clustered forest phenomena, ACS has been considered as an effective design for estimating density and total amount of the variable of interest (Thompson, 1990; 1991). Using ACS, one can focus measurements on areas with high damage intensity. If population groups are larger than sample plots, it is more efficient to measure and estimate the variables of interest using the ACS method (Acharya *et al.*, 2000). In many situations, the costs of a unit that do not satisfy the critical value C are lower than those of a plot that do. Moving from one sample plot to another takes time; if the plots are situated near each other the time spent on walking is decreased rapidly. However, one reason why ACS is seldom used in practice is that the sampling size is not known in advance. The risk that the sample size would become too large and thus, time-consuming, can be solved with restricted ACS (Brown and Manly, 1998). The restricted design allows the final sample size to be approximately determined before field sampling (Brown and Manly, 1998).

Here, the defoliation intensity estimates were quite similar in all sampling methods, which increases the need for careful evaluation of the effectiveness of the methods. The total population variance of ACS_{ST} was smallest because the sampling method takes into account prior information from the stratification. Both the ACS_{ST} and ACS_{SRS} methods allow measurement of additional units; in ACS_{SRS}, the outcome was calculated for the entire sample and the result showed a larger variance. Thus, the influence of prior information is significant. When each stratum is calculated separately, the results achieved are more precise. The SRS variance was nearly twice as large as that of ACS_{ST} and was not capable of competing with ACS methods for the effectiveness of inventorying insect-caused defoliation. The SRS method suffered from small sample sizes and the loss of taking adaptive measuring units. On the other hand, even if the SRS took the same number of sample plots into calculation, it would suffer from its ineffectiveness.

The CV describes the dispersion of the variable so that the variable's measurement unit is no object. Higher CV implies that there is greater dispersion in the variable. Here, CV also confirms the superiority of ACS_{ST} in inventorying *D. pini*-caused damage in comparison to ACS_{SRS} and SRS. The CV% of ACS_{SRS} was larger to some extent; again, that of SRS was significantly larger.

In ACS_{ST}, comparison between strata shows that peatland had the most homogenous sample plots. There were no seedling plots in the stratum, in which no or only slight defoliation intensity was found. If prior information is available, it is worth considering how to use it best in selecting the initial sample. Our results agree with those of de Somviele *et al.* (2004) in Palokangas: defoliation is lower in stands situated in more fertile forest site types. The largest cluster was found in the HP stratum, mainly situated in the seedling tree position, where there are appr. 20 trees per hectare. Such low densities can also constitute a risk of defoliation in more fertile productivity stands.

During late summer 2008, *D. pini* defoliation was relatively minor. There were only two plots in the final sample with defoliation intensities over 40%, and most of the initial sample plots had intensities under 20%. *Diprion pini*-caused defoliation has occurred in the Palokangas area for over a decade, fluctuating since that time. If the ACS method is used to inventorying the phenomenon, more sample plots would be measured in years when the defoliation is more intense.

Some of the sources of error in the fieldwork may have included measurement and positioning errors in locating and measuring the relascope sample plot. Yet, the effects of these errors could not be analytically observed in the results. Positioning errors can result in misidentified strata in plots when ACS_{ST} is used. However, due to the accurate positioning achieved with the global positioning system (GPS) device, there were no such problems in our field measurements.

The above-mentioned source of error can lead to the risk of misidentifying the variable of interest. In SRS, misidentifications may cancel each other, but in adaptive sampling they

accumulate. Thus, an adaptive sampling method should be employed for variables that can be identified with full confidence. Here, the critical variable was estimated visually, which could easily cause deviation in results if the surveyor were not a professional. Naked-eye calibration is essential when two or more researchers are estimating the critical variable.

Further studies will be focused on acquiring additional information by aerial photographs and laser-scanning data, thus bringing more information to the initial sample selection (Lyytikäinen-Saarenmaa *et al.*, 2008). Remote-sensing materials are valuable means for detecting and mapping insect damage in rare and clustered phenomena. In this study, stratification was performed according to the compartment-wise information from the study area. With remote-sensing data, the stratification could be carried out by focusing on more plots in areas where pest damage could already be detected from the material.

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Article

Vulnerability Assessment of Forest Ecosystem to Climate Change in Korea Using MC1 Model

Sungho Choi[*1], Woo-Kyun Lee[*1], Hanbin Kwak[*1], So-Ra Kim[*1], Seongjin Yoo[*1], Hyun-Ah Choi[*2], Sunmin Park[*2] and Jong-Hwan Lim[*3]

ABSTRACT

The objective of this study was to assess the vulnerability of forest ecosystem to climate change in Korea using MAPSS-CENTURY (MC1) model, one of Dynamic Global Vegetation Models (DGVMs). Also, it was to suggest selected and concentrated adaptation strategies for local government on the basis of this assessment. For the MC1 simulation of past years (1971-2000), the climatic data was prepared by the Korea Meteorological Administration (KMA). In addition, for the future simulation, the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5) coupling with atmosphere-ocean circulation model (ECHO-G) provided the future climatic data under the SRES (Special Report on Emission Scenario of IPCC) A1B scenarios. This study predicted the changes in vegetation distribution by climate change, and it analyzed the spatial and temporal variation of the Net Primary Production (NPP) and Soil Carbon Storage (SCS) using the MC1 model simulations. The vulnerability assessment of forest ecosystem can be divided into two categories; 1) the vulnerability of vegetation distribution and 2) the vulnerability of forest ecosystem function, such as the NPP and SCS. In addition, the sensitivity and adaption capacity were evaluated for each category. As results of the vulnerability assessment, relatively vulnerable areas were situated in the western coastal part and south eastern inland of Korea. Based on the spatial variation in vulnerability, we could suggest that the central and local governments need to prepare concentrated adaptation strategies for climate change based on the vulnerability assessment.

Keywords: climate change, forest ecosystem, vulnerability, MC1 model, Dynamic Global Vegetation Model

INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), mean annual global temperature has been inclined by 0.74℃ over the past 100 years, and it may be increased by 1.1-6.4℃ in the future 2090s (IPCC, 2007a). With the recent global warming, the IPCC (2007b) has considered that the climate change effect on forest ecosystem is one of major issues. The forest vegetation plays an important role in climate processes by its contribution to heat and moisture fluxes throughout the ecosystem. Therefore, it is important to evaluate the changes in forest ecosystem resulting from climate change (Arris and Eagleson, 1989; Ohsawa, 1993; Matsui *et al.*, 2004a; 2004b; Laurent *et al.*, 2004; Horikawa, 2009). Previously, many studies on dynamic global vegetation models (DGVMs) were conducted to understand the climate change effects on the ecosystem (Prentice *et al.*, 1992; Lenihan and Neilson, 1993; Brzeziecki, 1995; Cao and Woodward, 1998; Osborne *et al.*, 2000; Bachelet *et al.*, 2001; Watanabe *et al.*, 2004). The DGVMs simulate the changes in potential distribution of vegetation and its associated biogeochemical and/or hydrological fluxes due to climate change. The DGVMs simulate the annual or monthly dynamics of ecosystem processes. Their temporal and spatial resolutions depend on the time series of climate data and the given characteristics of latitude,

Corresponding author: Woo-Kyun Lee
E-mail: leewk@korea.ac.kr
[*1] Department of Environmental Science and Ecological Engineering, Korea University, Seoul, 136-713, Korea
[*2] Department of Climatic Environment, Graduate School of Life and Environmental Science, Korea University, Seoul, 136-713, Korea
[*3] Korea Forest Research Institute, Seoul, 130-712, Korea

topography, and soil data, respectively (Bachelet *et al.*, 2001). Especially, United States Department of Agriculture (USDA) has developed the MAPSS-CENTURY (MC1) model to assess the climate change effects on the ecosystem of California, USA (Lenihan *et al.*, 2003; 2008). Also, in China, the Carbon Exchange between Vegetation, Soil, and Atmosphere (CEVSA) model predicted the potential vegetation distribution changes due to climate change (Yu *et al.*, 2006).

Many researchers have tried to apply previous DGVMs , such as the Holdridge (Kim and Lee, 2006), CEVSA (Lee *et al.*, 2007a), and MC1 (Choi *et al.*, 2009a), to assess the vulnerability of Korean forest ecosystem using the past and future climatic data, even though there were no national vegetation models in Korea (Kim *et al.*, 2008). Practically, these models have limitations to provide accurate results for the regional scale of Korea, because most of them were designed and tested at the global or the continental scale, and Korea has more heterogeneous topography and climate, compared to global level (Lee *et al.*, 2007a; Kim *et al.*, 2009; Choi *et al.*, 2009a). However, due to the simple and clear processes of the MC1 model and CEVSA model, it is possible to use Geographic Information System (GIS) application and understand the sub-modules related to ecosystem mechanisms. In other words, these models are suitable to scrutinize the ecosystem vulnerability to climate change (Bachelet *et al.*, 2001; Yu *et al.*, 2006).

To assess the vulnerability of forest ecosystem to climate change, it requires several of information. Also, the indicators in vulnerability assessment should be comprehensive for each component of the forest ecosystem. The mechanisms of sensitivity and adaptation capacity are not completely clarified and it is hard to quantify the effect of each indicator on the vulnerability of forest ecosystem. However, principal component analysis (PCA) can be applied for vulnerability assessment, which compounds the related indicators and produces the newly synthetic indicators (Han *et al.*, 2006). According to Lenihan *et al.* (2008), the MC1 can simulate the potential vegetation distribution, Net Primary Production (NPP) and Soil Carbon Storage (SCS). Also, it can assess the vulnerability of forest ecosystem due to climate change from the understanding of the sensitivity and adaptation capacity, related to the ecosystem structure, i.e. potential distribution, and the function, i.e. NPP and SCS.

For last three decades, the forest management policy pursues the sustainable management in Korea. Recently, corresponding to United Nations Framework Convention on Climate Change (UNFCCC), Korean government has prepared a master plan to expand the forest as a source of carbon sinks, and have constructed related statistical database. Moreover, for more effective conservation and management of the forest ecosystem, it is important to have the systemic monitoring and to designate the long-term ecological research area and special protection area (Han *et al.*, 2007). In other words, the climate change assessment of vulnerability using the DGVMs is aiming to minimize the negative effects of climate change on forest ecosystem, and it is required to predict the highly vulnerable area to enhance the adaptation capacity to climate change.

In this study, we analyzed the vulnerability of Korean forest ecosystem using the MAPSS-CENTURY (MC1) model based on the past and future climatic data. The assessment of vulnerability for forest ecosystem was divided into the two categories; the vulnerability of the vegetation distribution and forest ecosystem function, such as NPP and SCS. Also, it evaluated the sensitivity and adaptation capacity for each indicator.

MATERIAL AND METHOD

The MC1 Model

The MC1 model is a DGVM to assess the climate change effects on ecosystem structure and function. It includes three modules, such as the biogeographic module - MAPSS (Neilson, 1995), biogeochemistry module - modified CENTURY (Parton *et al.*, 1987), and fire module – MCFIRE (Lenihan *et al.*, 1998). This model can routinely generate simulations of tens to hundreds of years period on spatial data grids with cell sizes ranging from 900m^2 to about 2,500km^2 (Bachelet *et al.*, 2004). As shown on Fig. 1, it simulates 1) the plant life-form and vegetation classes, 2) the movement of carbon, nitrogen, and water fluxes for ecosystem, and 3) fire disturbance, respectively (Bachelet *et al.*, 2001). Also, it has two modes of equilibrium (static) and transient (dynamic) using climatic and soil information. It results in potential vegetation distribution using the life-form interpreter, and the NPP and SCS using the CENTURY model algorithm, respectively. The results of MC1 model simulations were validated at the previous study of Bachelet *et al.* (2008). Compared to the observed data of NPP across the US, the MC1 model results were fairly reasonable to be verified, even though it provided over and/or under-estimated results for some study sites. In this study, it used the default parameters and thresholds of the MC1 model, even though, sometimes, it needs to optimize the model parameters when we apply the DGVMs to simulate the smaller region, such as Korea.

Study Area and Data Preparation

The study area was located in South Korea, 124°54′~131°06′ at longitude and 33°09′~38°45′ at latitude. Topographical characteristics of study area are shown in digital elevation model (Fig. 2a). The Taebaek Mountain Range elevates to over 1,500 m on the eastern side of Korea. From the Taebaek Mountain Range, the Sobaek Mountain Range runs from northern east to southern west. In the central zone, moderately high mountains dominate the landscape. Elevations are generally low, because these mountain ranges have been subjected to long-term erosion with relatively stable tectonic movements (National

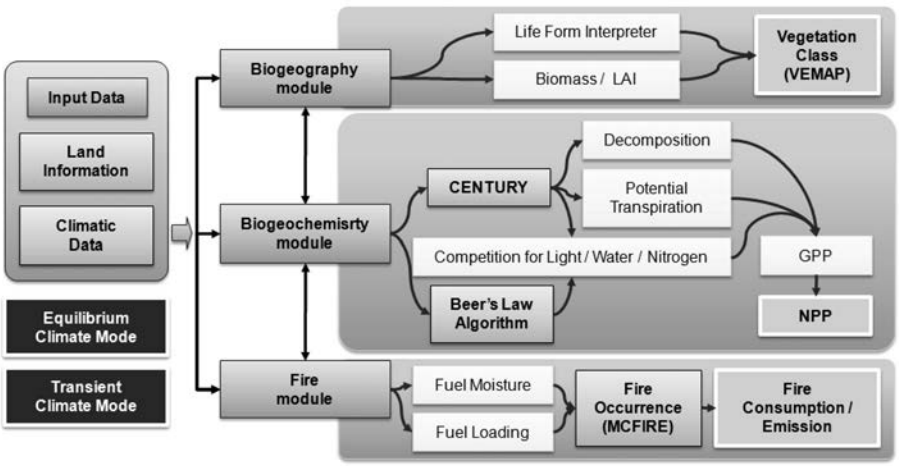

Fig. 1 The structure of the MC1 model
source: BACHELET *et al.* (2001).

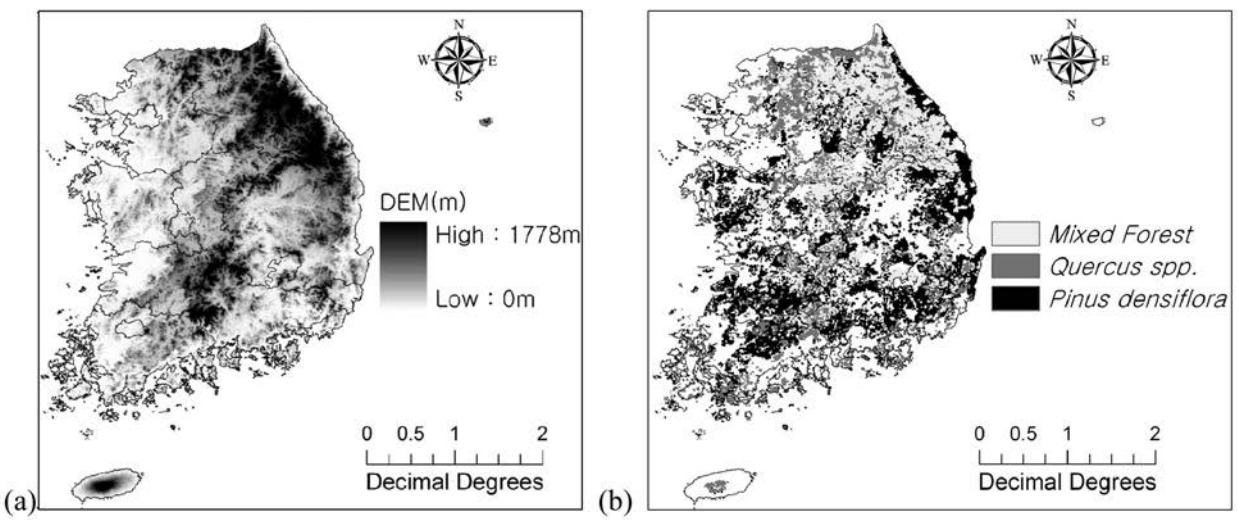

Fig. 2 (a) The Digital Elevation Model of Korea derived from National Geographic Information Institute and (b) the Actual forest type map from Korean Forest Service

GEOGRAPHIC INFORMATION INSTITUTE, 2007). As shown in Fig. 2b, evergreen needle-leaved forests (mainly *Pinus densiflora*) and deciduous broad-leaved forests (mainly *Quercus* spp.) occupy approximately 42% and 26% of the total forest area in 2008, respectively (KOREA FOREST SERVICE, 2009). These species are major tree species in Korea and they are important in terms of ecological, economical, and socio-cultural values (LEE *et al.*, 2006).

For the overall simulations, the MC1 needed two categories of input data, such as climatic and ancillary data. In terms of climatic dataset, seven climatic factors were needed to be prepared; they were cumulative precipitation, monthly mean temperature, mean daily maximum and minimum temperature, vapor pressure, wind speed, and solar radiation. Ancillary dataset included general geographical information, such as elevation, latitude, absolute area, and soil information, such as soil bulk density, soil texture, mineral depth, and rock fragment.

The temporal ranges of this study were assigned into three periods of 1) the past (1971-2000), 2) near future (2021-2050), and 3) far future (2071-2100). Korea Meteorological Administration (KMA) provided climatic data obtained by 75 weather stations across South Korea for the past years between 1971 and 2000. These data were interpolated with Inverse Distance Squared Weighting (IDSW), one of the spatial statistic methods, regarding the absolute temperature lapse rate by altitude (LEE *et al.*, 2007b). In addition, the anomalies of the future climatic data were predicted by the Fifth-Generation NCAR / Penn State Mesoscale Model (MM5) model coupling with atmosphere-ocean circulation model (ECHO-G) by A1B scenario (Special Report on Emission Scenario of IPCC) from National Institute of Meteorological Research (NIMR) in 0.2432° (about 27km) of

grid size (MIN *et al.*, 2006; CHA *et al.*, 2007). To construct the ancillary data, the elevation, latitude, and absolute area data were achieved from the digital map of the National Geographic Information Institute (NGII). Also, soil information, i.e. soil bulk density, soil texture, mineral depth, and rock fragment, were provided by the Food and Agriculture Organization (FAO) and International Soil Reference and Information Centre (ISRIC). These datasets were rescaled to fit on 0.01° (about 1km) spatial resolution in the World Geodetic System (WGS-84) coordination system and applied to produce the future climate data based on the past climatic data (LEE *et al.*, 2007b).

Assessment of Vulnerability

The vulnerability was defined as the range or scope of damage to nature or society system by climate change (IPCC, 2007b). This was estimated by relations between sensitivity and adaptation capacity as the indicators for the vulnerability assessment. The high sensitivity means the high vulnerability; reversely the low adaptation capacity means the high vulnerability (YU *et al.*, 2006; YU, 2006; LEE *et al.*, 2007a). This could be represented as following function (Eq. (1));

$$V = S - A, \tag{1}$$

where V is the vulnerability, S is the sensitivity, and A is the adaptation capacity.

Assessment of vulnerability - potential vegetation distribution

In the MC1 model, the vulnerability of vegetation distribution and forest ecosystem functions, i.e. NPP and SCS, were estimated and integrated into the indicator of vulnerability of Korean forest. Each of them was estimated with sub indicators, such as the sensitivity and adaptation capacity in Eq. (1). In the vulnerability assessment of the potential vegetation distribution, the sensitivity to climate change was decided by the changing frequency of vegetation classes (or types) in each grid. For example, the changing frequency will increase, if there is once vegetation type change in a grid when the certain type of vegetation is not suitable for the provided climate condition (YU *et al.*, 2006; YU, 2006; LEE *et al.*, 2007a; HAN *et al.*, 2007). The high changing frequency was assumed as the high sensitivity. The adaptation capacity could be estimated using the changing direction which was defined as two directions, such as positive (+) and negative (-) direction (YU *et al.*, 2006; YU, 2006; LEE *et al.*, 2007a; HAN *et al.*, 2007). The positive changing was assumed to array from the mixed forest to the broad-leaved and needle-leaved forest in terms of maintenance of species diversity, because the needle-leaved forest has been reported to be likely to reduce the area by increase of temperature (KONG, 2005; KIM and LEE, 2006). The positive changing was assumed to be the high adaptation.

Assessment of vulnerability - forest ecosystem function (NPP and SCS)

According to the assessment of vulnerability for the forest ecosystem function variables, such as the NPP and SCS, the sensitivity and adaptation were respectively described as the variability and changing trend (YU *et al.*, 2006; LEE *et al.*, 2007a; HAN *et al.*, 2007). The variability of forest ecosystem functions was estimated with the average values for the study period and whole period (1970-2100). The variability of each period implied as the differences between the values of study year and the average value for whole simulation term. It was described below (Eq. (2));

$$D_n = \frac{\sum_{i=1}^{j} \left| V_{ni} - \overline{V_n} \right|}{\overline{V_n}}, \tag{2}$$

where D is the variability of forest ecosystem functions for whole period (years), V_i is the value of forest ecosystem function variable in study year i, $\overline{V}$ is the average value of the forest ecosystem function variable for whole period (years), and n is a grid of the study site.

The adaptation capacity of forest ecosystem functions was estimated with the change trend of variability of forest ecosystem function variables, such as the NPP and SCS (YU *et al.*, 2006; YU, 2006; LEE *et al.*, 2007a; HAN *et al.*, 2007). Decreasing of the trend of variability means that the system is apt to be stabled to climate change, which can be described as the more adaptive (Eq. (3)). On the other hand, the increase of the trend means the forest ecosystem function variables were less stable and much more vulnerable to climate change. The trend of the forest ecosystem annual variability was represented as the slope of the linear trend lines fitting to the variability of the forest ecosystem functions in the study period (YU *et al.*, 2006; YU, 2006; LEE *et al.*, 2007a; HAN *et al.*, 2007).

$$Y = aX + b, \tag{3}$$

where Y is the variability of the study period, X is the study period, and a is the change trend of forest ecosystem function variables.

As shown in Fig. 3, this method can explain the sensitivity and adaptation capacity of forest ecosystem function. For example, in comparison of two test sites, such as A (Fig. 3a) and B (Fig. 3b), we assumed that a temporary variable of ecosystem function was simulated for 25 years (Hypothetical period). The average values were assumed as 18.6 and 18.24 for the site A and B, respectively. In terms of the sensitivity, the site A was more sensitive than the site B, because the site A (Fig. 3c) had the larger sum of differences between the values for each year and the average for whole years, compared to the site B (Fig. 3d). On the other hands, in terms of the adaptation capacity, the site A was more adaptive than the site B, because the variability trend (slope) of site A (Fig. 3e) was negative (-0.0015:

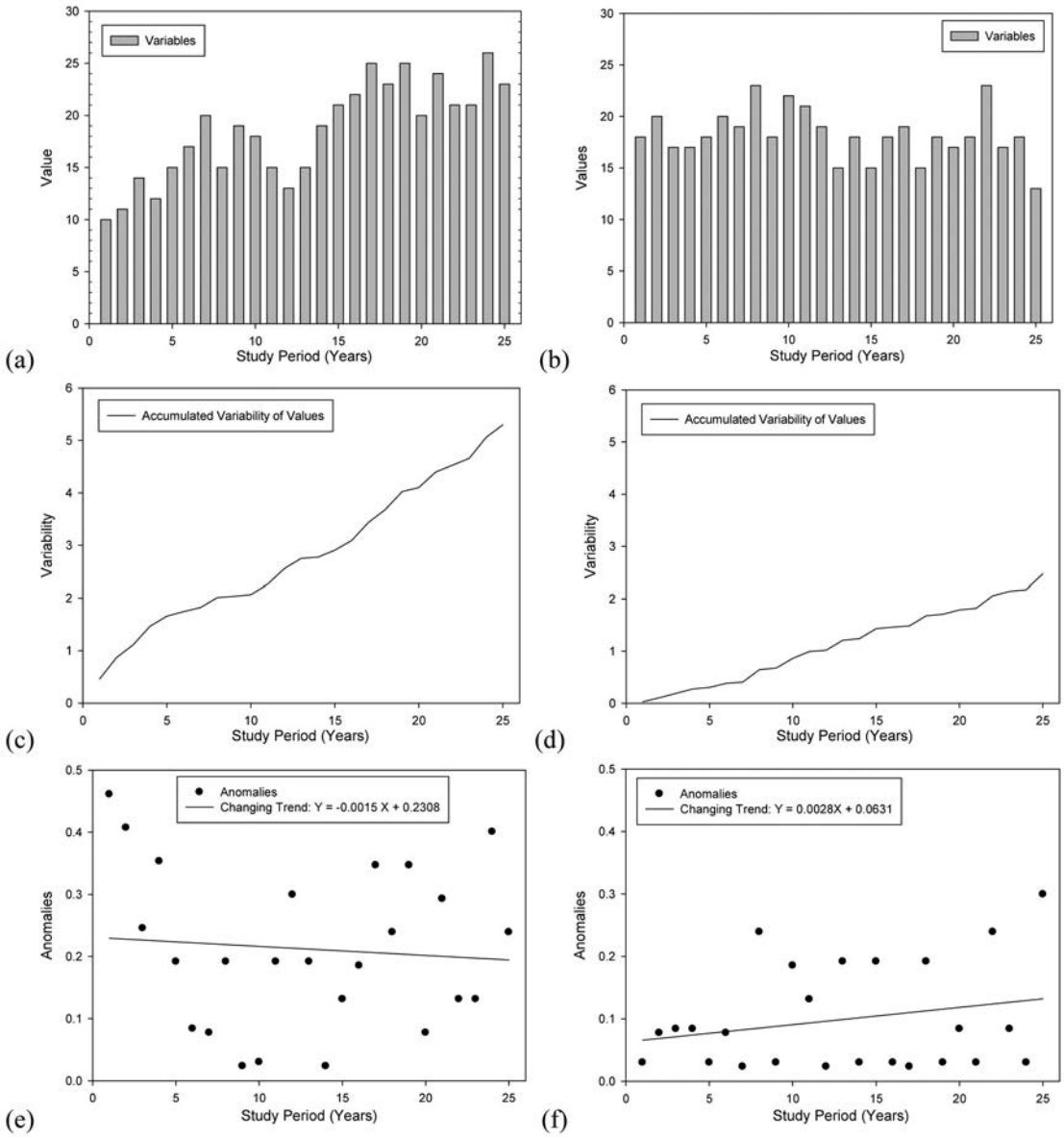

Fig. 3 Examples of sensitivity and adaptation capacity for a temporary variable of ecosystem function

decrease of the variability for each year) and the trend of site B (Fig. 3f) was positive (0.0028: increase of the variability for each year).

Integrated vulnerability of forest ecosystem distribution and function

To assess the vulnerability of Korean forest ecosystem, using the above indicators, the overall vulnerability of forest ecosystem was assessed by integrated indices, e.g. the vulnerability of both forest ecosystem distribution and functions. In the integration of indicators, we normalized the values of vulnerability for forest ecosystem distribution and forest ecosystem function (Eqs. (4) and (5)). In this study, we classified the vulnerability, sensitivity, and adaptation capacity into five categories, depending on their normalized ranges, such as "very high: 0.8-1.0", "high: 0.6-0.8", "moderate 0.4-0.6", "low: 0.2-0.4", and "very low: 0.0-0.2". Also, the vulnerability of forest ecosystem was assessed with Principal Component Analysis (PCA) to calculate the degree of vulnerability (Table 1).

$$ {}_{n}V = \frac{X - X_{mn}}{X_{mx} - X_{mn}}, \tag{4} $$

where ${}_{n}V$ is the normalized vulnerability, X is the estimated vulnerability, X_{mn} is the minimum value of vulnerability, and X_{mx} is the maximum value of vulnerability.

Table 1 The scheme of vulnerability assessment of forest ecosystem

Categories of vulnerability		Indicators	Sub-indicators	Description
Forest Ecosystem Vulnerability	Vulnerability of vegetation distribution	Changes in forest type	Changing frequency	Sensitivity
			Changing trend	Adaptability
	Vulnerability of forest ecosystem function	NPP	Variability	Sensitivity
			Trend of variability	Adaptability
		SCS	Variability	Sensitivity
			Trend of variability	Adaptability

*From the assessment process of YU *et al.* (2006).

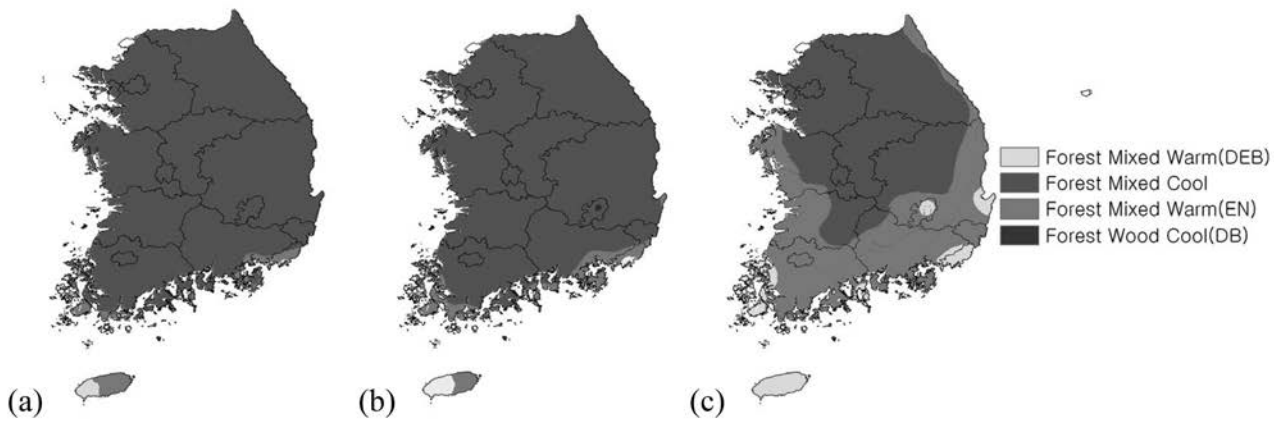

Fig. 4 (a) the MC1 Simulation of the potential vegetation distribution of past (1971-2000), (b) near future (2021-2050), and (c) far future (2071-2100)

*EN: Evergreen Needle-leaved dominant; **DEB: Deciduous and Evergreen Broad-leaved dominant; ***DB: Deciduous Broad-leaved dominant.

Table 2 Proportion of potential vegetation distribution in area (km²) and ratio (%)

Forest types	Past	Near future	Far future
Cool mixed forest	****95,214 (96.06)	92,351 (93.18)	55,117 (55.61)
*Warm mixed forest (EN)	3,252 (3.28)	5,549 (5.60)	38,634 (38.98)
**Warm mixed forest (DEB)	648 (0.65)	1,140 (1.15)	5,348 (5.40)
***Forest hard wood cool (DB)	1 (0.00)	75 (0.07)	16 (0.02)
Total	99,115 (100.00)	99,115 (100.00)	99,115 (100.00)

*EN: Evergreen Needle-leaved dominant; **DEB: Deciduous and Evergreen Broad-leaved dominant; ***DB: Deciduous Broad-leaved dominant; ****Area in km² (Ratio in %).

Table 3 Changing frequency of each period in area (km²) and ratio (%)

Changing frequency	From past to near future	From near future to far future
Changed	*3,354 (3.38)	40,150 (40.51)
Unchanged	95,761 (96.62)	58,965 (59.49)
Total	99,115 (100.00)	99,115 (100.00)

*Area in km² (Ratio in %).

$$_nV_E = {}_nV_D + {}_nV_F, \quad (5)$$

where $_nV_E$ is the normalized forest ecosystem vulnerability, $_nV_D$ is the normalized vulnerability of the forest ecosystem distribution, and $_nV_F$ is the normalized vulnerability of the forest ecosystem function.

RESULTS AND DISCUSSION

Vulnerability of the Vegetation Distribution

Potential vegetation distribution of past and future

Fig. 4 depicts the simulated potential vegetation distribution of past (1971-2000), near future (2021-2050), and far future (2071-2100) using the MC1 model.

As results of the predicted potential vegetation distribution of past years (1971-2000), Korean ecosystem was mostly occupied by the cool mixed forest, the needle-leaved dominant (EN) warm mixed forest, and the broad-leaved dominant (DEB) warm mixed forest, and their proportions were 96.06%, 3.28%, and 0.65%, respectively. The cool mixed forests were occupying the most part of Korea and the EN warm mixed forest was existed in southern coast and the Jeju Island. In near future, the composition of forest types were 93.18% of the cool mixed forest, 5.60% of the EN warm mixed forest, and 1.15% of the DEB warm mixed forest. Compared to the past years, the EN warm mixed forests were expanding to northward, and the DEB warm mixed forests, which existed in only Jeju area, were appeared in southern metropolitan cities, such as Busan, Pohang, and Dae-Gu. In far future, there was no great change in overall composition of vegetation type, but distribution ratio was changed. The cool mixed forests were decreased down to 55.61% and the EN warm mixed forests were increased up to 38.98% (Table 2). This result was correspondent to the result of research by LEE *et al.* (2007a).

Vulnerability of vegetation distribution

To assess the vulnerability of vegetation distribution, it estimated the changing frequency and changing direction in terms of sensitivity and adaptability, respectively. As results of the sensitivity estimation for vegetation distribution, the future climate would not provide the suitable climatic condition for vegetations existed in the past years (Table 3), and 3.38% of the study area was exposed to be changed from past to near future. Also, there were vegetation composition changes in 40.51% of area from near future to far future. As the integrated changing frequencies above, the sensitivity of whole years (1971-2100) was derived in Table 3 and Fig. 5b.

From the results of predicting adaptation capacity of vegetation distribution, 3.38% of study area was likely to change to negative (-) direction from past to near future and 40.43% was changed to negative direction from near future to far future. Especially, some of region (1.30%) will be exposed to two steps of negative direction (-2) - from the cool mixed to the DEB

Table 4 Changing direction of each period in area (km²) and ratio (%)

Changing direction	From past to near future	From near future to far future
Positive direction (+1)	-	73 (0.07)
No changes	*95,761 (96.62)	58,965 (59.49)
Negative direction (-1)	3,279 (3.31)	38,771 (39.12)
Negative direction (-2)	1 (0.00)	1,292 (1.30)
Negative direction (-3)	74 (0.07)	14 (0.01)
Total	99,115 (100.00)	99,115 (100.00)

*Area in km² (Ratio in %).

Table 5 Sensitivity, adaptation capacity, and vulnerability of vegetation distribution in area (km²) and ratio (%)

Sensitivity Adaptation Capacity Vulnerability	Changing frequency	Changing direction	Overall vulnerability
Very High (0.8~1.0)	*1,174 (1,18)	1 (0.00)	1,190 (1.20)
High (0.6~0.8)	-	56,785 (57.29)	1,293 (1.30)
Moderate (0.4~0.6)	41,156 (41.52)	39,846 (40.20)	39,846 (40.20)
Low (0.2~0.4)	-	2,467 (2.49)	-
Very Low (0.0~0.2)	56,785 (57.29)	16 (0.02)	56,786 (57.29)
Total	99,115 (100.00)	99,115 (100.00)	99,115 (100.00)

*Area in km² (Ratio in %).

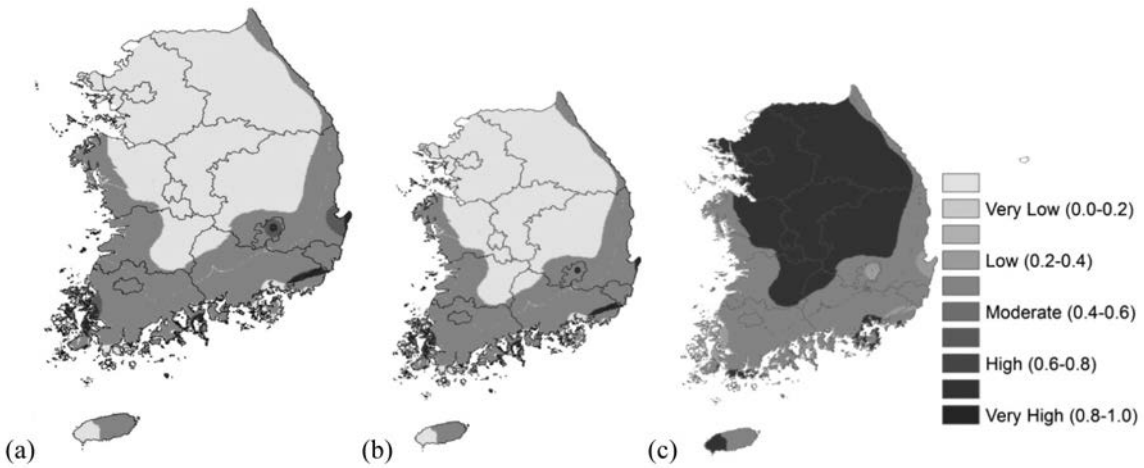

Fig. 5 (a) Vulnerability of vegetation distribution, (b) Sensitivity, and (c) Adaptation Capacity of vegetation distribution
*Vulnerability of vegetation distribution = Sensitivity (Changing frequency) - Adaptation Capacity (Changing direction).

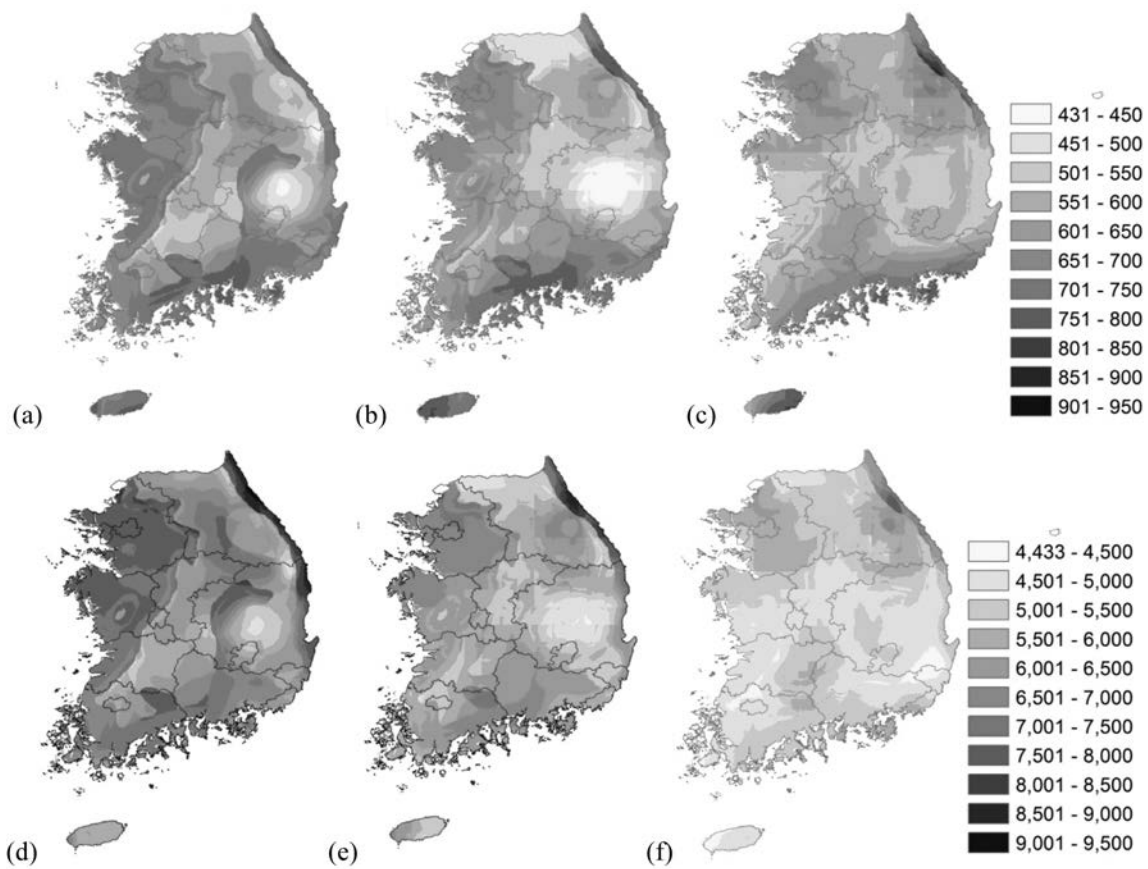

Fig. 6 (a) MC1 Simulated potential NPP distribution of past (1971-2000), (b) near future (2021-2050), and (c) far future (2071-2100), and (d) potential SCS distribution of past, (e) near future, and (f) far future

Table 6 Variability and changing trend of NPP and SCS in area (km^2) and ratio (%)

Sensitivity Adaptation Capacity	Variability		Changing trend	
	NPP	SCS	NPP	SCS
Very High (0.8~1.0)	-	-	1,252 (1.26)	2,067 (2.09)
High (0.6~0.8)	-	132 (0.13)	3,878 (3.91)	16,746 (16.90)
Moderate (0.4~0.6)	*2,271 (2.29)	19,020 (19.19)	50,921 (51.38)	55,202 (55.69)
Low (0.2~0.4)	30,695 (30.97)	62,231 (62.79)	41,023 (41.39)	24,205 (24.42)
Very Low (0.0~0.2)	66,149 (66.74)	17,732 (17.89)	2,041 (2.06)	895 (0.90)
Total	99,115 (100.00)	99,115 (100.00)	99,115 (100.00)	99,115 (100.00)

*Area in km^2 (Ratio in %).

warm mixed forest (Table 4). From the changing directions, the adaptation capacity of whole year (1971-2100) was estimated in table 5 and Fig. 5c.

The vulnerability of vegetation distribution can be assessed by the integration of the sensitivity and adaptation capacity. The higher changing frequency and the negative trend of changing direction are comprehended as the high vulnerability of vegetation distribution. As results of the integration of above results, some part of southern inland area and western and eastern coastal areas (2.50% of study area) were exposed to the "Very high" or "High" vulnerability (Fig. 5a and Table 5). It is assumed that the mean monthly temperatures would increase by 4.1-4.6℃ in far future and the accumulated precipitation in growing season would be 1.5-2.8 times higher in far future than in past (1971-2000). However, other study area was exposed to the "Very low" vulnerability (57.29%) and the "Moderate" vulnerability (40.20%) of vegetation distribution.

Vulnerability of Forest Ecosystem Function

Potential NPP and SCS distribution of past and future

Fig. 6 depicted the simulated NPP and SCS distribution in past, near future, and far future. The potential vegetation production and carbon storage in soil were simulated by the MC1 using soil temperature and moisture derived from the climatic information, and nitrogen availability derived from the soil information. The NPP of past was ranged from 430.93 to 796.28 $gC \cdot m^{-2} \cdot yr^{-1}$ and the average was 647.90 (std. dev. 73.99) $gC \cdot m^{-2} \cdot yr^{-1}$. Compared to the past, the range of the overall estimated NPP would be changed in near future (376.33-827.27 $gC \cdot m^{-2} \cdot yr^{-1}$) and far future (498.53-901.59 $gC \cdot m^{-2} \cdot yr^{-1}$). Also, the average of NPP would decrease to 609.02 $gC \cdot m^{-2} \cdot yr^{-1}$ in near future and 599.70 $gC \cdot m^{-2} \cdot yr^{-1}$ in far future. On the other hands, the average of SCS in past was 6,810.5 (std. dev. 784.0) $gC \cdot m^{-2}$. The SCS was ranged from 4,720.5 to 9,478.2 $gC \cdot m^{-2}$ in past. As similar as the NPP, the average value of the SCS would decrease to 6,008.8 $gC \cdot m^{-2}$ in near future (range: 4,432.0-9,042.4 $gC \cdot m^{-2}$) and 5,154.5 $gC \cdot m^{-2}$ in far future (range: 3,930.5-8,493.9 $gC \cdot m^{-2}$) due to climate change.

Vulnerability of forest ecosystem function

To assess the vulnerability of forest ecosystem function, it estimated variability and changing trend of the NPP and SCS in terms of sensitivity and adaptation capacity, respectively. As results of sensitivity estimation for forest ecosystem function, overall variability of the NPP and SCS was relatively low. More than 80% of study area was classified as the "Low" or "Very low" of variability (e.g. 97.71% for the NPP and 80.68% for the SCS). In other words, the forest ecosystem functions did not respond to climate change sensitively, compared to the sensitivity of vegetation distribution. Conversely, in terms of adaptation capacity, the change trends of variability for the NPP and SCS were likely to be "Moderate" or "Low" adaptability (e.g. 92.77% for the NPP and 80.11% for the SCS) (Table 6).

The vulnerability of forest ecosystem function could be assessed by the integration of sensitivity and adaptation capacity of the NPP and SCS. The higher variability and the positive changing trend were comprehended as the high vulnerability of forest ecosystem function. As results of integration of above results, western coastal and inland areas were exposed to the "Very high" or "High" vulnerability (0.92% of study area). However, 85.14% of study area was exposed to the "Very low" or "Low" vulnerability (Fig. 7 and Table 7). This is assumed that mineral depth of the vulnerable area was deeper than 40cm and the bulk density of the vulnerable area was greater than 1.09 g/cm^3, compared to other area. The characteristics could be combined with precipitation and they are related to soil moisture and hydrological values which highly affect on the NPP and SCS (Bachelet *et al.*, 2001).

Vulnerability of Forest Ecosystem

With the integration of vulnerability for vegetation distribution and forest ecosystem function, the overall vulnerability of forest ecosystem was evaluated for forest ecosystem in Korea. As shown Fig. 8 and table 8, 50.61% of Korea was exposed to the "Very low" vulnerability of forest ecosystem. However, some part of Korean ecosystem would be exposed to the "Very high" or "High" vulnerability in southern west and east coastal area and southern east land area due to climate change

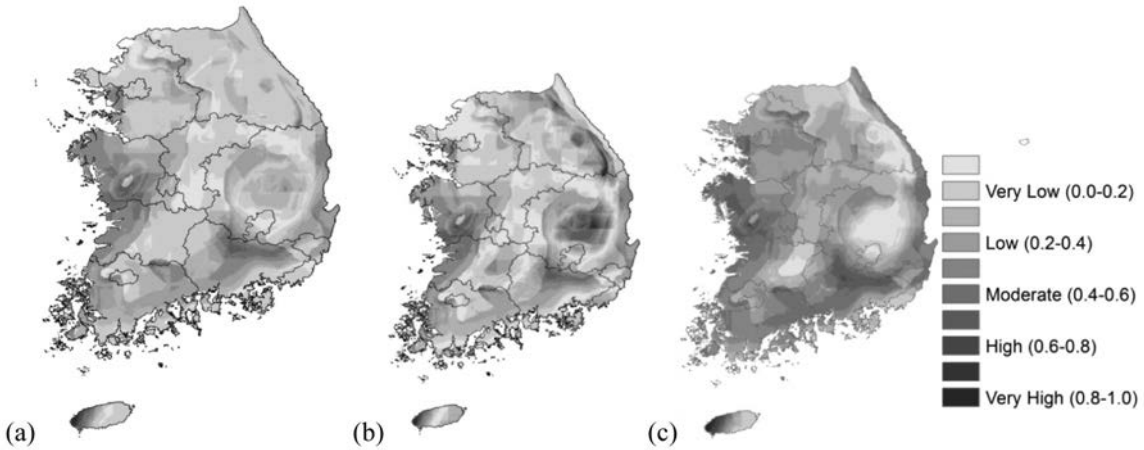

Fig. 7 (a) Vulnerability of forest ecosystem function (NPP+SCS), (b) NPP and (c) SCS vulnerability
*Vulnerability of forest ecosystem function = NPP vulnerability + SCS vulnerability.

Table 7 Vulnerability of forest ecosystem function - NPP and SCS in area (km^2) and ratio (%)

Vulnerability of forest ecosystem function	NPP	SCS	Integrated NPP and SCS
Very High (0.8~1.0)	*349 (0.35)	205 (0.21)	106 (0.11)
High (0.6~0.8)	2,770 (2.79)	4,354 (4.39)	806 (0.81)
Moderate (0.4~0.6)	15,416 (15.55)	37,637 (37.97)	13,817 (13.94)
Low (0.2~0.4)	35,326 (35.64)	41,431 (41.80)	33,652 (33.95)
Very Low (0.0~0.2)	45,254 (45.66)	15,488 (15.63)	50,734 (51.19)
Total	99,115 (100.00)	99,115 (100.00)	99,115 (100.00)

*Area in km^2 (Ratio in %).

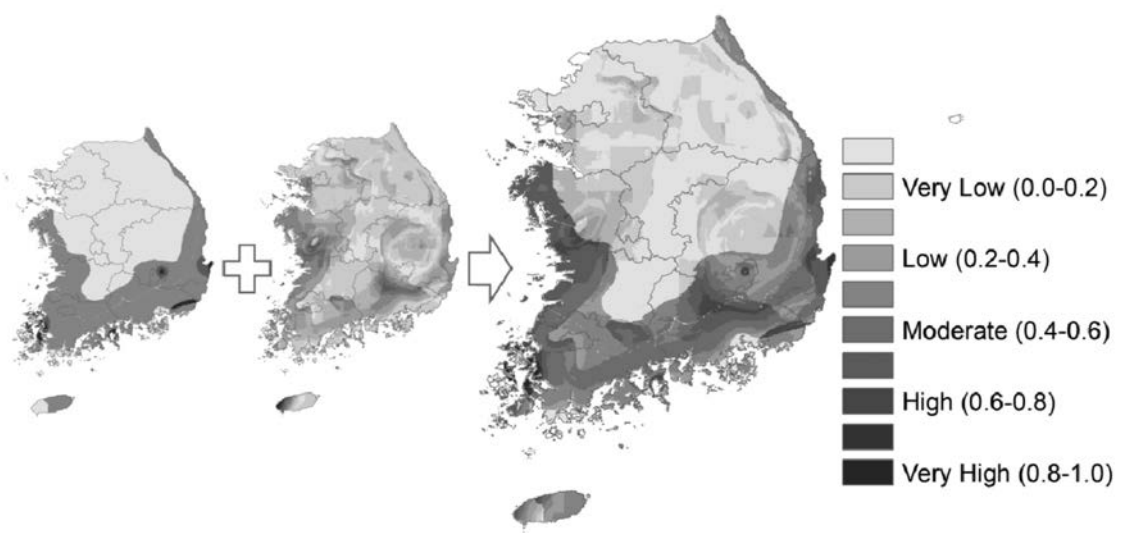

Fig. 8 Vulnerability of forest ecosystem
*Vulnerability of vegetation distribution + Vulnerability of forest ecosystem function = Vulnerability of forest ecosystem.

Table 8 Vulnerability of forest ecosystem in area (km^2) and ratio (%)

Vulnerability	Overall vulnerability of forest ecosystem
Very High (0.8~1.0)	603 (0.61)
High (0.6~0.8)	11,011 (11.11)
Moderate (0.4~0.6)	26,208 (26.44)
Low (0.2~0.4)	11,129 (11.23)
Very Low (0.0~0.2)	50,164 (50.61)
Total	99,115 (100.00)

*Area in km^2 (Ratio in %).

(11.72% of study area). In this high vulnerable area, both vegetation distribution and forest ecosystem function were sensitive to climate change and were exposed to less adaptation capacity. The reasons of high vulnerability could be 1) the increase of monthly mean temperature and minimum temperature, i.e. two of threshold for life-form interpreter of the MC1 model, 2) the soil condition influencing the vegetation production and soil carbon storages (Bachelet *et al.*, 2001), even though these reasons should be validated in future research.

The vulnerability of vegetation distribution was evaluated to be higher than that of forest ecosystem function in Korea. In the study of Lee *et al.* (2007a), the forest ecosystem was assessed with CEVSA model. They also resulted in relative high vulnerability of vegetation distribution, compared to the vulnerability of forest ecosystem function. However, the MC1 model, as one of the DGVMs, has limitation that it cannot perfectly explain the relatively heterogeneous topography and micro-climate of Korea. Also, the MC1 performance for Korean ecosystem could not be validated with the field observed NPP and SCS data at the plot-scale. The vegetation and carbon dynamics are significantly affected by natural disturbance, such as fires, in the MC1 run at the country scale, whereas carbon changes due to the fires are infrequent and difficult to quantify at the plot-scale (Bachelet *et al.*, 2008). So, it could be discrepant between the model results and field measurements. In addition, the MC1 model did not consider the direct anthropogenic effects on forest ecosystem. Therefore, the results of vulnerability assessment in this study needs to be supplemented by optimizing the previous models and developing Korea-specific vegetation model. To optimize and develop the Korea-specific model, it is required to apply the Warmth Index (Yim, 1977), mean minimum temperature of the coldest month (MTC), summer and winter precipitation (Horikawa *et al.*, 2007), and slope and direction of topography algorithms (Lee *et al.*, 2006). Recently, Choi *et al.* (2009b) have conducted on a study to predict vegetation distribution by climate change using the WI and MTC, and in further research, they will develop regional scale model related to terrestrial carbon fluxes. It would be one of useful complementary source for forest ecosystem vulnerability assessment.

CONCLUSIONS

This study analyzed the overall vulnerability of Korean forest ecosystem by the integrated assessment of vulnerability of both vegetation distribution and forest ecosystem function using the MAPSS-CENTURY (MC1) model based on the past and future climatic data. Korean ecosystem was mostly occupied by the cool mixed forest, the warm mixed forest (Evergreen Needle-leaved dominant: EN), and the warm mixed forest (Deciduous and Evergreen Broad-leaved dominant: DEB). Their proportions were 96.06%, 3.28%, and 0.65%, respectively. Southern inland area and western and eastern coastal areas (11.72% of study area) were exposed to the very high or high vulnerability of forest ecosystem. Also, 61.84% of study areas have the "Very low" or "Low" vulnerability of forest ecosystem. Overall vulnerability of forest ecosystem in Korea was in the "Low" or "Moderate" level. However, Korean ecosystem would be exposed to the high vulnerability in southern west coastal area and southern east land area due to climate change. According to Kong (2005) and Kim and Lee (2006), in the high vulnerable area to climate change, the forest vegetations are easily exposed to the heat stress or drought and they are likely to die off due to the changes in forest climate region. Also, unsuitable environmental condition for forest growth and breeding would lead the reduction of forest production and the degradation of forest vegetation. Based on the spatial variation in vulnerability, we could suggest that the central and local governments need to prepare concentrated adaptation strategies for climate change based on the vulnerability assessment. However, these studies, using DGVMs, has limitation that it is difficult to consider the heterogeneous topography and micro-climate of Korea and the direct anthropogenic effects on forest ecosystem. Therefore, the results of vulnerability assessment in this study needs to be supplemented by optimizing the previous models and developing the Korea-specific vegetation model.

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Article

Spatial Distribution and Radial Growth Response of *Pinus densiflora* to Climatic and Topographic Factors in Central Urban Forest of Seoul, Korea

Hyun-Ah Choi[*1], Woo-Kyun Lee[*1,2], Jae-Gyun Byun[*2], Han-Bin Kwak[*2], So-Ra Kim[*2] and Woo-Hyuk Byun[*2]

ABSTRACT

Recently, several studies have shown relationships between tree radial growth and climatic factors. It is generally assumed in dendroclimatological studies that there exists relationship between tree radial growth and the climatic factors. In this study, we analyzed the relationship between tree radial growth of *Pinus densiflora* and climatic factors that had been collected from sample sites in central urban area, Seoul in Korea. Based on sensitivity analysis of radial growth using a variety of combinations of independent variables, temperature has a positive effect on radial growth. The standard growth appeared better in the north and south aspects where the mean temperature was higher than other aspects. This study also indicated that spatial autocorrelation existed in standard growth with the range of 250m, indicating thatthere exist spatial differences in tree growth due to micro climatic and topographical variability. This result can be used to develop accurate regional process based model for reasonable management of urban forest.

Keywords: *Pinus densiflroa*, radial growth, dendroclimatology, spatial distribution, spatial autocorrelation

INTRODUCTION

Climate is often considered one of the most prominent and consistent factors affecting year to year variability in tree growth and depending on the existence of other growth limiting factors (FRITTS, 1976). Due to the limited time interval of instrumental climate records, many natural proxies have been used to conduct paleoclimatic reconstruction. Tree rings have been widely used to reconstruct the variability of many climate factors (e.g., temperature, precipitation), due to their annual resolution, wide spatial distribution, and the possibility of using simple linear models of climate-tree growth relationships that seem to be easily verified and calibrated (HUGHES, 2002).

As climate change begins to have significant impacts (OGDEN and INNES, 2007), monitoring their magnitude and direction will be required to adapt forest management practices to these impact. It is generally assumed in dendroclimatological studies that there exists close relationship between tree growth and climate factors (FRITTS, 1976). FRITTS *et al.* (1965) demonstrated that values of ring width correlation and variation can also be used as a basis for evaluating the growth response of a stand to its environment. In addition, dendrochronological and dendroclimatological methods are useful tools for revealing the dominant factors influencing radial growth (FRITTS, 1976; COOK and KAIRIUKSTIS, 1990) and demonstrate some of their advantages particularly for obtaining more detailed, annual resolution data on forest growth and stand dynamics.

Variability in tree growth response to climate across geographical gradients can be anticipated due to varying site requirements for different species (FOWEELS, 1965) and differences in soils reflected in moisture availability and nutrient

Corresponding author: Woo-Kyun Lee
E-mail: leewk@korea.ac.kr
[*1] Department of Climatic Environment, Graduate School of Life and Environmental Science, Korea University, Anamdong5ga SungbukKu, Seoul 136-713, Korea
[*2] Department of Environmental Science and Ecological Engineering, Graduate School, Korea University, Anamdong5ga SungbukKu, Seoul 136-713, Korea

content (PRITCHEETT and FISHER, 1987; KIM and SICCAMA, 1987; BASSETT, 1964) local fluctuations in climate not accounted for in available data (DAUBENMIRE, 1974; HAINES and CLEVELAND, 1981). Spatial variability is, of course, a function of scale. However, variability in forest ecosystem can be extreme, as conditions influencing tree growth can change substantially over a small area (SMITH *et al.*, 1991). Spatial analysis at a small scale was conducted to allow an interpolation of climate-tree-growth relationships (OBERHUBER *et al.*, 1998).

This study aims to investigate relationship between tree growth and climatic, topographic factors in Mt. Nam of central urban forest in Seoul. In addition, spatial variability is examined using the geostatistical model of relationship between climatic variables and annual growth.

MATERIALS AND METHODS

Study Area

The study area was Nam Mountain (39°32′N～37°33′N and 126°58′E～127°00′E) which is located in the central part of Seoul. It is confronted with wasted heat emitted from automobile, residence and building (MIN, 2007). Its forest ecosystem has been impacted by the air pollution from 1970s (SUH *et al.*, 1997). The ridge of the mountain is mainly dominated by the deciduous tree species, and red pines are growing as isolated islands in the stands of northern and western slopes (KIM, 1994).

Tree Sampling and Tree Ring Data

This study was conducted to reveal the effects of micro climatic and topographical factor on *Pinus densiflora* (red pine) growth of Mt. Nam in Seoul. For this, we used the 148 tree-ring data of red pines from 4 compartments and 6～12 sub-compartments in pine trees (Fig. 1). We sampled this stand as part of our studies on the growth and dynamics of pine trees in the region. Core samples were extracted with an increment borer at breast height (1.2m above ground) from opposite sides of each tree and processed in usual way (PILCHER, 1990). Tree age was estimated from tree ring number and DBH (Diameter at Breast Height) was measured at the height of core extraction.

Topographic and Climatic Factors

As a topographic factor, TWI (Topographic Wetness Index) was prepared using GIS-supported TWI-module (MOORE *et al.*, 1991; LEE *et al.*, 2000).

$$TWI = \ln (A / (C \tan\beta)), \quad (1)$$

where A is total upslope area; C is the contour length of the border between adjacent cells; $\tan\beta$ is an angle of inclination.

Fig. 1 Study area: Nam Mountain in Seoul, Korea

Table 1 Description of the variables used in the growth model

Variables	*Pinus densiflora* (148 stems)			
	Mean	Min	Max	SD
Growth (mm)	2.28509	0.47	5.947	1.10416
Age (year)	43.34459	17	99	19.55586
DBH (cm)	17.49324	6	42	7.0378
TWI*	3.0134	1.68101	5.89972	0.81
Temperature (℃)	11.82048	11.47536	12.27577	0.14474
Humidity (%)	71.68488	67.15084	76.67615	1.72488

*TWI, Topographic Wetness Index.

Table 2 Predicted growth models

Function	Considered variables	Model
1	age+size	$SRG = a_0 DBH^{a1} \cdot age^b$
2	age+size+site	$SRG = a_0 DBH^{a1} \cdot age^b \cdot TWI^{c1}$
3	age+size+climate	$SRG = DBH^{a1} \cdot age^b \cdot e^{e1 \cdot T} \cdot H^{e2}$
4	age+size+site+climate	$SRG = DBH^{a1} \cdot age^b \cdot TWI^{c1} \cdot e^{e1 \cdot T} \cdot H^{e2}$

* SRG, Standard Radial Growth; TWI, Topographic Wetness Index; T, Temperature; H, Humidity.

For climate data, we used the annual mean temperature and humidity data provided by KMA (Korean Meteorological Administration) and a fixed-station transect of temperature sensors (HOBOs) data in Mt. Nam. The spatial climatic data of sample plots was prepared by interpolation of IDW (Inverse Distance Weight), one of the spatial statistic methods. Description of the variables used in this study is shown in Table 1. In this study, we predicted growth model for analyzing the relationship between tree radial growth and topographic, climatic factors (Lee, 1996; Lee *et al.*, 2004; Byun *et al.*, 2009).

Standard Radial Growth

In the routine of tree ring analysis, the samples collected at one site are standardized and the results are averaged into a site chronology (NOAA, 2008). Thus we applied tree-ring standardization methods for analyzing the relationship between measured tree radial growth and climatic, topographic factors. In this study, we derived 10 year's average radial growth (Δ_r) function over age with following power function using SAS program (Lee, 1996; SAS, 2000; Byun *et al.*, 2009).

$$\Delta_r = a \cdot Age^b \tag{2}$$

With this function, standard radial growth (SRG) was derived for analyzing spatial variation of radial growth.

$$SRG = \Delta_r \times \left(\frac{30}{Age}\right)^b, \tag{3}$$

where *SRG* is standard radial growth (mm); Δ_r is radial growth; b is coefficient.

Spatial Autocorrelation of SRG (Standard Radial Growth)

Variogram analysis (Bailey and Gatrell, 1995; Mowrer and Congalton, 2000; Webster and Oliver, 2001; Lee *et al.*, 2006) was employed to identify the spatial autocorrelation and variability of standard radial growth using the S+SPATIAL STATS module of SPLUS (Kaluzny *et al.*, 1998).

Relationship between SRG and Topographic and Climatic Factors

Several regression functions (Table 2) was fitted to the data set for analyzing relationship between SRG and topographic, climatic factors.

RESULTS AND DISCUSSION

The relationship between radial growth and tree age was shown in Fig. 2. Radial growth has decreasing tendency with tree age as usual.

Spatial distribution of standard radial growth is shown in Fig. 3. The standard radial growth appears better in the northern and southern aspect where the mean temperature was higher than other aspect. The mean temperature of northern and southern aspect showed a slightly higher than other slope. However, humidity has opposite trend.

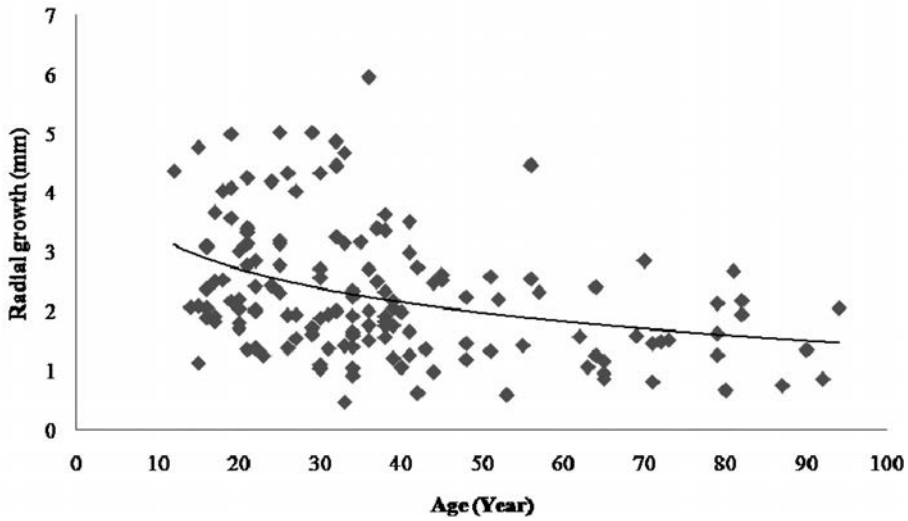

Fig. 2 Relationship between radial growth and tree age
The curve is estimated curve.

It showed that the best-fit variogram model for our study is the spherical variogram model with the nugget 0.7774 and sill 0.3800. Spatial autocorrelation existed in standard radial growth within a range of about 250m, suggesting that standard radial growth can be spatially similar within 250m (Fig. 4).

The parameter estimates and related statistics for the relationship between SRG and TWI, temperature, and humidity are presented in Table 3 and Fig. 5. The models show relatively reasonable performance in explaining the variation in radial growth, all with coefficient of determination (R^2) ranging from 0.36 to 0.37.

Based on this sensitivity analysis of radial growth using a variety of combinations of independent variables, the conclusion could be reached that the temperature has a positive effect on radial growth, while the other variables such as age, TWI, humidity a negative influence.

This study developed a model of tree growth response to topographic and climatic factors using tree ring data. Our model indicates that TWI, temperature, and humidity can be the limiting factors for red pine growth at Mt. Nam in Seoul. In whole function, temperature is proven to have positive impact on red pine growth with relatively high statistical significance, while TWI and humidity shows negative impact with low statistical significance.

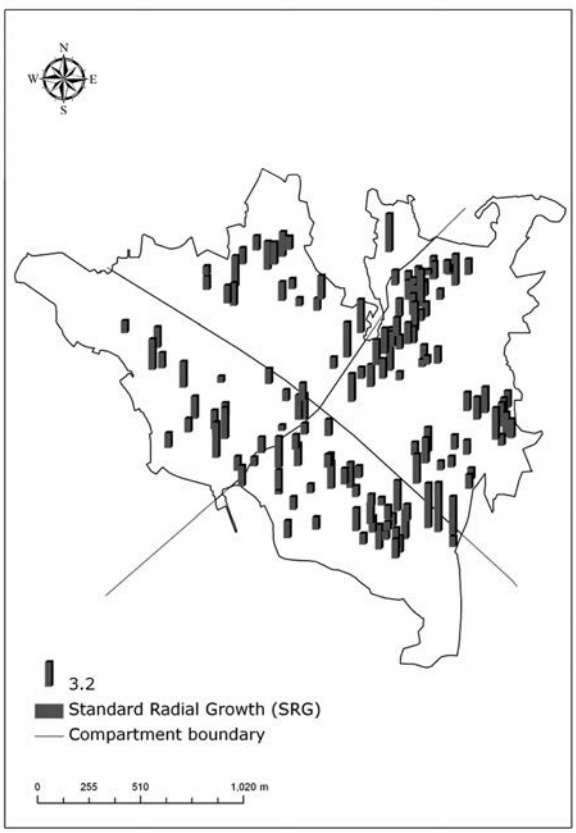

Fig. 3 Spatial distribution of standard radial growth (SRG)

CONCLUSION

In this study, we analyzed the relationship between red pine growth and TWI, temperature, and humidity in MT. Nam in central Seoul. And we developed models using a variety of combinations of independent variables. The models explain the variation in radial growth, with R^2 ranging from 0.36 to 0.37. Based on models, the conclusion could be reached that the

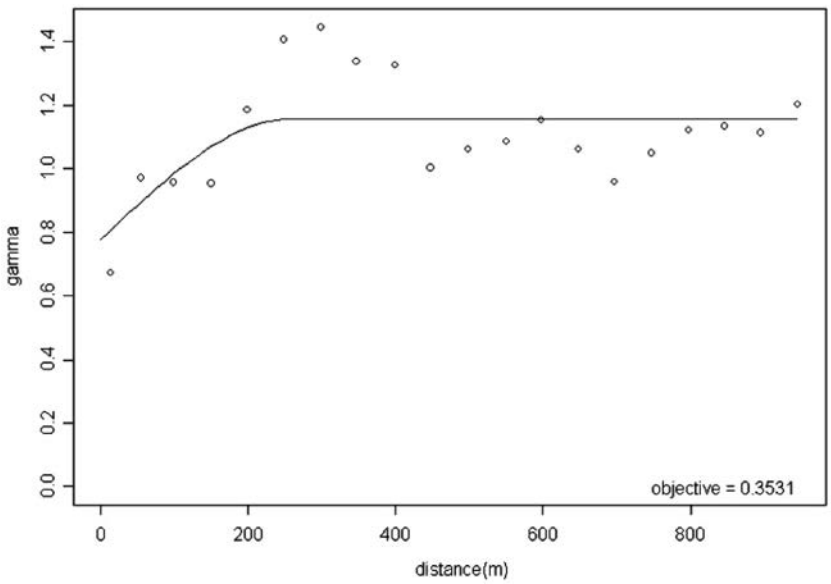

Fig. 4 Variogram of standard radial growth (SRG)

Table 3 Parameter estimates and related statistics for radial growth predicted model

Function	Coefficient		Std error	*t*-value	R^2
1	a0	8.830	2.598	3.399	0.358
	a1	0.706	0.100	7.035	
	b	−0.913	0.106	−8.584	
2	a0	9.869	3.074	3.210	0.362
	a1	0.723	0.103	7.029	
	b	−0.925	0.107	−8.612	
	c1	−0.106	0.113	−0.932	
3	a1	0.701	0.101	6.948	0.366
	b	−0.903	0.106	−8.492	
	e1	0.252	0.148	1.709	
	e2	−0.193	0.414	−0.467	
4	a1	0.712	0.104	6.856	0.367
	b	−0.911	1.076	−0.847	
	c1	−0.065	0.117	−0.557	
	e1	0.225	0.152	1.476	
	e2	−0.100	0.433	−0.232	

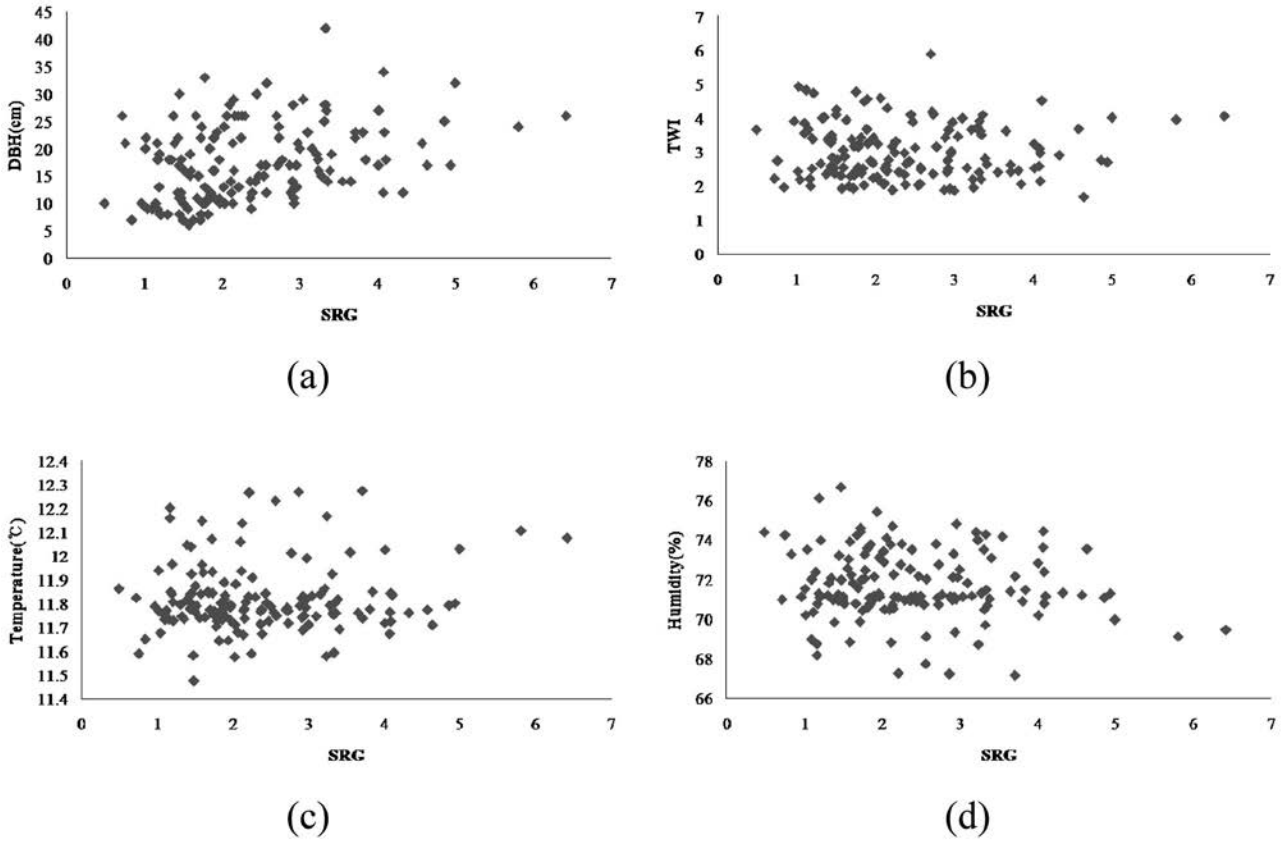

Fig. 5 Relationship between standard radial growth (SRG) and parameters: (a) DBH, (b) TWI, (c) temperature, (d) humidity

temperature has positive effect on radial growth with relatively high statistical significance, while TWI and humidity has negative effect with low statistical significance. In addition, this study indicated that spatial autocorrelation existed in standard radial growth within a range of about 250m. This means that there exist spatial differences in tree growth due to micro climatic and topographical variability.

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Article

Relationship between Climate and Radial Growth of *Pinus parviflora* var. *pentaphylla* on Mountain Ridges under Thick Snow in Tohoku, Japan

Tatsuya Sasaki[*1], Yoshihiro Nobori[*1] and Maximo Larry Lopez Caceres[*2]

ABSTRACT

In this study, *Pinus parviflora* var. *pentaphylla* trees from four ridges (sites) on Mount Gassan in Yamagata Prefecture were sampled for tree-ring analysis. Two cores were collected from each of the 32 individuals sampled. After confirming the synchronization of tree-ring-width fluctuations within each site and among sites, correlation coefficients were calculated between tree-ring-width fluctuations and monthly climate data for precipitation, snowfall, daylight duration, and average temperature. *t*-values of the synchronization of tree-ring width among sites were higher than 3.46, indicating a significant correlation at the 0.1% level. Synchrony was not significantly different among sites. The range of synchronization was estimated to be within a radius of 14 km. The correlation coefficients between the tree-ring-width index and meteorological data for the previous year in December, January snowfall, and April temperature were significant at the 1% level. Our results suggest that *P. parviflora* var. *pentaphylla* trees from mountain ridges provide reliable information on past climate events and are thus suitable for assessing dendroclimatology.

Keywords: dendroclimatology, snowfall, *Pinus parviflora* var. *pentaphylla*, ridge, tree-ring width

INTRODUCTION

Annual tree-rings are influenced by and therefore record multiple environmental factors (Fritts, 1976). Long-term environmental fluctuations that affect tree growth can be inferred from tree-ring analysis (Fritts, 1976). Previous studies have shown strong relationships between tree-rings and climate factors (Kobayashi *et al.*, 1992; Nobori, 1994; Yasue, 1997). Until now, only long-lived and easily accessed trees have been used for studies on dendroclimatology (Nobori, 1994; Yasue, 1997; Sawauchi *et al.*, 2007). But, there is no paper that has focused on the growth microtopography of trees. For example, it is expected that trees that grow along damp stream are affected by precipitation, trees that grow along thirsty ridges are affected by daylight and temperature. Like this, there is a possibility that trees that grow characteristic position have original physiological characteristic.

Tohoku district in Japan is characterized by *Pinus parviflora* var. *pentaphylla*, the northern variety of *P. parviflora* distributed from southern Hokkaido to central Honshu (Hayashi, 1969). This variety grows on ridges, where the soil is barren (Maeda and Yoshioka, 1951). Few papers have examined the ecology of *P. parviflora* var. *pentaphylla* in Tohoku district. Sugita and Kudo (1994) showed that *P. parviflora* var. *pentaphylla*, *Thujopsis dolabrata* (Thunb. ex L.f.) Siebold & Zucc. and *Tsuga diversifolia* (Maxim.) Masters forests on Mount Hayachine were strongly related to disturbances such as timber cutting. But, dendroclimatological research on *P. parviflora* var. *pentaphylla* is limited to Kato (2008). He studied the relationships between radial growth and climate factors on a slope of Mount Tate and showed that radial growth in *P. parviflora* var. *pentaphylla* on Mount Tate is inhibited by snow.

The purpose of this study was to analyze the relationships between radial growth in *P. parviflora* var. *pentaphylla* and climate factors in Tohoku district in Japan.

Corresponding author: Yoshihiro Nobori
E-mail: ynobori@tds1.tr.yamagata-u.ac.jp
[*1] Faculty of Agriculture, Yamagata University, 1-23 Wakabamachi, Tsuruoka 997-8555, Japan
[*2] Faculty of Agriculture, Iwate University, 3-18-8 Ueda, Morioka 020-8550, Japan

SITES AND SAMPLING METHODS

Four sites were chosen on the western portion of Mount Gassan in Yamagata Prefecture. The location of each site is as follows: site 1 (38° 33′ 29.14″ N, 139° 55′ 41.33″ E), site 2 (38° 33′ 29.14″ N, 139° 55′ 41.33″ E), site 3 (38° 29′ 35.62″ N, 139° 58′ 50.35″ E), and site 4 (38° 29′ 31.59″ N, 139° 58′ 47.07″ E). The sites had an average altitude of 700 m. In the past, this forest was used for charcoal production (Asahi Village History Editing Committee, 1985; Nishikawa Town History Editing Committee, 1995). The azimuth of the ridgeline ranged from 208° to 265° and pointed westward. All of the ridges in this study were dominated by *P. parviflora* var. *pentaphylla*.

Two core samples were collected at breast height from each of eight trees per site. Cores were taken using 5-mm and 10-mm-increment borers in March 2008.

Samples were processed and scanned (Epson, GT-X700) with a resolution of 2,400 dots per inch. Tree-ring widths were measured with Dendro Measure 106 (Nobori, 2005). The accuracy of measurements was approximately 0.01 mm, and the most recent tree-ring was for 2007.

Cross-dating was performed using COFECHA (Holmes, 1983). Tree-ring-width data were standardized using ARSTAN (Holmes, 1983; Cook, 1985) to remove the effect of growth trends. Standardization of data was conducted for each site and the data were averaged to remove competition effects among trees. Standardization has two purposes: the first is to remove non-climate factors from the data and the second is to obtain tree-ring information relative values that are not influenced by the size of the measured value. The filter year for the cubic spline was 8.

To evaluate agreement between tree-ring fluctuations, ARSTAN output statistical data were calculated. ARSTAN output statistical data include the mean sensitivity (mean of the relative difference between one tree-ring value and the next one), the between trees (mean of the correlation coefficient between individuals), trees vs mean (mean of the correlation coefficient between an individual and the master chronology), the signal-to-noise ratio (rate of explained fluctuations divided by unexplained fluctuations or the residual), agreement with population chronology (agreement with the master chronology for each individual), variance in the first eigenvector (rate of variance in the first eigenvector), the chronology common interval mean (mean of the common interval in the chronology), and the chronology common std dev (standard deviation of the common interval in the chronology).

A *t*-value for tree-ring-width synchronization was calculated using the following equation:

$$t = |r|\sqrt{(N-2)/(1-r^2)}, \quad (1)$$

where t is the *t*-value, r is a correlation coefficient, and N is the number of tree-rings. The larger the *t*-value is, the higher the agreement will be between one tree-ring fluctuation and another. After agreement of the data was confirmed within a site, a master chronology was calculated using the tree-ring data and the agreement of each site's master chronology was compared among sites. The master chronology is a series that includes the average of several standardized tree-ring data series that are representative of the site (Kaennel and Schweingruber, 1995).

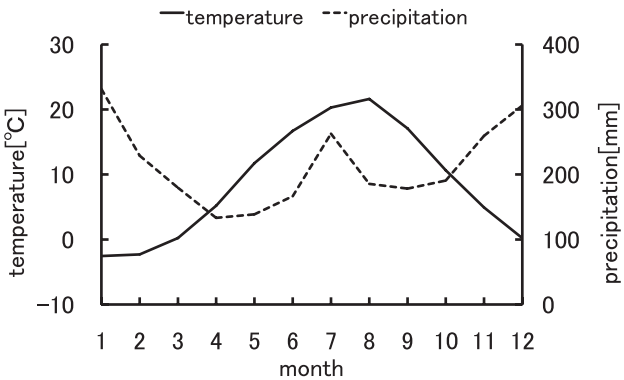

Fig. 1 Climate graph at Ooisawa (statistical time is 24 years from 1984 to 2007)

To evaluate the relationships between tree-ring fluctuations in *P. parviflora* var. *pentaphylla* and climate factors, we used a simple correlation analysis between the master chronology and the climate data. Climate data from the Meteorological Agency Observatory at Ooisawa, Yamagata (Fig. 1), were used in this study. The observatory is at an altitude of 440 m and is 20 km away from our sites. The climate data included the monthly average temperature, total precipitation, total daylight duration, and snowfall. Annual climate data spanned from October in the preceding year to September in the target year. This annual pattern was selected because climate factors after September affect radial growth, and radial growth ends during September. To extract a high correlation with the master chronology, climate data were also standardized to remove possible climate change trends. The purpose of this study was not to reconstruct past climate, but to analyze the suitability of using *P. parviflora* var. *pentaphylla* for studying dendroclimatology. Therefore, our focus was not on the measured values but on the standardized values for correlations. We used 24 years of standardized climate data and tree-ring-width index series spanning from 1984 to 2007.

RESULTS AND DISCUSSION

Area Agreement

The number of tree-rings ranged between 72 and 108. The *t*-value for the mean agreement of tree-ring fluctuations is shown in Table 1. Since the *t*-values for all combinations among sites were larger than the significance level of 0.1%, tree-ring fluctuations were assumed to agree among sites. ARSTAN

Table 1 *t*-values for comparisons of tree-ring fluctuations between sites

site	site 2	site 3	site 4
site 1	5.22	4.01	6.15
site 2		6.89	6.99
site 3			9.63

$N > 60$, $t > 3.46$ and $t_{\alpha} > {}_{0.001}$

Table 2 ARSTAN statistical output

Mean correlations	All sites
Mean sensitivity	0.21
Between trees	0.29
Trees vs mean	0.50
Signal to noise ratio	20.18
Agreement with population chron.	0.95
Variance in first eigenvector	0.33
Chron. Common interval mean	0.99
Chron. Common std dev.	0.10

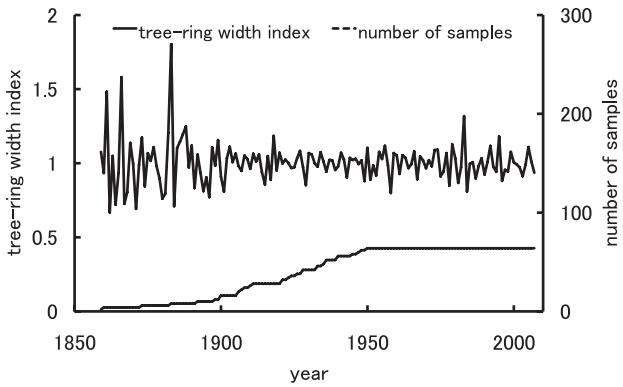

Fig. 2 Master chronology of tree-ring width

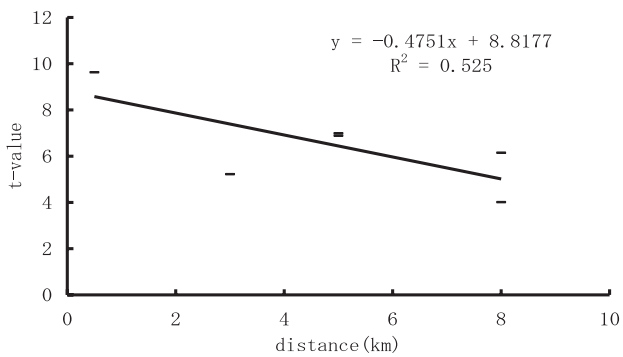

Fig. 3 Correlation between the *t*-value for tree ring width synchronization and distance between sites

output statistics for tree-ring chronology (Table 2) showed that means sensitivity ranged between 0.124 and 0.185. The mean correlation coefficient among all trees was higher than the critical value of 0.36. Agreement within the population chronology was higher than 90%. Variance in the first eigenvector was 40～50%. The master chronologies calculated by ARSTAN extracted sufficiently common tree-ring fluctuations from all trees. The ARSTAN output statistics showed stronger agreement than was observed with *T. dolabrata* in Aomori (SAWAUCHI *et al.*, 2007). Therefore, tree-ring fluctuations are likely affected by consistent climate factors throughout the entire area. Master chronologies were averaged among sites, and tree-ring fluctuations and climate factors were analyzed for correlations. We divided tree-ring widths by a standardization function to obtain a tree-ring index (Fig. 2). Values higher than 1 indicate that the year's radial growth is active and values lower than 1 indicate that the year's radial growth is inactive (KAENNEL and SCHWEINGRUBER, 1995).

Relationships between *t*-values for Tree Ring Width Synchronization and Distance

The *t*-values for tree-ring width synchronization are negatively correlated with the distance between sites (MITSUTANI, 1987; SAWAUCHI and NOBORI, 2005). We therefore decided to analyze the relationship between *t*-values and distance.

The minimum distance between sites was 0.5 km (site 3-site 4) and the maximum distance was 8 km (site 1-site 3, site 1-site 4). The correlation coefficient between *t*-values and distance was −0.72, which was significant at the 5% level (Fig. 3). The regression was calculated with the following formula:

$$y = -0.4751x + 8.8177, \quad (2)$$

where x is the distance between sites and y is the *t*-value. These results suggest that *t*-values are negatively correlated with the distance between sites. According to this regression formula, the longer the distance is among sites, the lower the agreement will be in tree-ring fluctuations. Therefore, we determined that agreement in *P. parviflora* var. *pentaphylla* tree-ring fluctuations on Mount Gassan occurs within a radial range of 14 km. At distances longer than 14 km, *t*-values may be lower than 2 (not significant at the 5% level). *T. dolabrata* tree-ring fluctuations agreed at a range of 75 km (SAWAUCHI and NOBORI, 2005). *P. parviflora* var. *pentaphylla* tree-ring fluctuations agreed in smaller areas than *T. dolabrata*, but large area data are needed to refine this analysis.

Tree-Ring Information and Climate Factors

P. parviflora var. *pentaphylla* grows on ridges and in locations that have a lot of gravel, where the ground dries quick-

Table 3 Correlation between the master chronology and monthly climate data

	month											
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
precipitation	−0.08	−0.12	−0.17	−0.07	0.15	0.16	0.07	0.16	−0.29	0.14	0.15	0.19
snowfall		−0.01	−0.55**	−0.49**	0.37	0.11	0.20	−0.41				
delight duration	0.09	0.01	0.19	0.12	−0.37	−0.26	−0.10	0.15	0.00	−0.12	−0.15	0.09
temperature	0.33	0.34	0.44*	0.35	0.23	0.37	0.50**	0.25	−0.29	−0.24	0.30	0.28

* $\alpha < 0.05$, ** $\alpha < 0.01$

ly, although precipitation during the growth phase (from March to September) does not affect radial growth (Table 3). Snowfall during the previous December and January of the target year were negatively correlated, but precipitation during the same phase was not correlated (Table 3). Precipitation is defined as any amount of water that falls as rain, snow, or hail, and snowfall is defined as the depth of snow that falls within a given period. Thus, snowfall provides a different amount of precipitation and will affect radial growth differently from rain. The altitude of our study sites was 700 m and the maximum snow depth was approximately 4 m. This heavy snow is bound to affect radial growth.

Temperature in April was positively correlated with radial growth, but the remainder of the growth phase was not correlated. We provide two interpretations for how temperature in April affects radial growth. First, April temperatures can affect photosynthesis. Generally speaking, photosynthesis is proportional to temperature at low temperatures and decreases at high temperatures (MIYACHI, 1992). The temperature changes during the growth phase (from March to September), however, did not affect radial growth at the study sites, and thus radial growth was the same at different temperatures. Annual variability in the number of days in April when the temperature exceeds 5 ℃ is very large (average = 15.13, standard deviation = 5.58). We estimated that temperature in April affected radial growth because of annual variability in the number of days in the growth phase. Second, April temperatures can correlate with a snow effect, because snow on the ground can restrain rising temperature. The low temperature would restrain radial growth. But snowfall at April did not correlate with temperature (r = −0.13, p = 0.52). There is low possibility that temperature at April correlate with snow. From the above, the temperature in April was apparently positively correlated with radial growth because temperature affected photosynthesis, and did not affect snow.

After calculating correlations between temperature and snowfall in December and January, correlation coefficients and p-values were r = −0.76 and p = 0.0000027 in December, and r = −0.52 and p = 0.0045 in January. The correlation coefficients were higher than those for radial growth. Therefore, temperature for each month was positively correlated with radial growth because it was a contrived correlation. From the above, the temperature in December and January positively affected radial growth because the temperature negatively affected snowfall. KATO (2008) showed that radial growth in *P. parviflora* var. *pentaphylla* on Tateyama is inhibited by snow, which agrees with the results of this study.

From our results, snowfall appears to inhibit radial growth and temperature in April appears to promote it. *P. parviflora* var. *pentaphylla* grows on ridges, and trees are hypothesized to grow in these areas to avoid the effects of snow. The inhibition of radial growth by snow concurs with the results of KATO (2008). As for the temperature in April, air temperature has been reported to be an important factor for restarting cambium activity in *Picea glehnii* in Hokkaido (YASUE, 1997). The same result was found in this study. The initial temperature increase in spring appears to be an important factor for trees in northern Japan.

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Article

Empirical Models for Estimating the Stand Biomass of Teak Plantations in Java, Indonesia

Tatang Tiryana[*1, 2], Satoshi Tatsuhara[*1] and Norihiko Shiraishi[*1]

ABSTRACT

The development of empirical biomass models has gained a great deal of attention during recent decades. These models have been constructed to facilitate the quantification of forest biomass and carbon sequestration benefits, but few empirical models exist for estimating the stand biomass of teak (*Tectona grandis* L.f.) plantations. This study therefore sought to develop stand-level biomass models that use minimum input data for teak plantations in Central Java, Indonesia. Stand biomass and other stand variables were derived from forest inventory data in Balo (Kebonharjo, Central Java). We used linear and nonlinear regression to develop four types of biomass models: volume to biomass, basal area to biomass, age to biomass, and age and basal area to biomass. These models were then validated using an independent data set. Results indicated that teak stand biomass was accurately estimated using the volume-to-biomass model. In addition, while the accuracy of the age and basal area-to-biomass model was comparable to that of the volume-to-biomass model, the basal area-to-biomass and age-to-biomass models were less accurate. Depending on the availability of input data, at least one of these models will be appropriate for estimating teak stand biomass. Thus, these models should prove quite valuable in supporting the multipurpose management of teak plantations in Java.

Keywords: teak plantations, biomass, carbon, stand-level model, multipurpose management

INTRODUCTION

Teak (*Tectona grandis* L.f.) is a naturalized plantation species in Java, Indonesia, that was introduced by Hindu monks probably in the fourteenth century (Behaghel, 1999; Krishnapillay, 2000; Nair, 2000; Pandey and Brown, 2000). Teak is a comparably dominant species that accounts for 62.3% of the total area of plantations in Java (Perum Perhutani, 2006a). For decades, teak plantations have provided economic benefits for the country because of their high timber prices, but a lack of information still exists regarding the environmental benefits of teak plantations, especially related to their effectiveness as carbon sinks.

The importance of quantifying forest biomass to estimate carbon stocks of a forest ecosystem has been stressed not only in the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (Brown, 2002) but also in various criteria and indicators for sustainable forest management. At the national and forest management unit (FMU) levels, the estimation of carbon stocks should be conducted periodically during forest resource assessments to ensure the sustainability of total forest benefits to society (ITTO, 2005). Various quantitative tools are obviously required to produce reliable estimates of forest biomass or carbon stocks. For teak plantations in Java, such tools remain scarce, which adds to the difficulty in evaluating the environmental benefits of plantations.

A common method for estimating forest biomass is the use of biomass models based on either tree-wise or stand-wise da-

Corresponding author: Tatang Tiryana
E-mail: tangtir@ipb.ac.id
[*1] Graduate School of Agricultural and Life Sciences, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-8657, Japan
[*2] Department of Forest Management, Faculty of Forestry, Bogor Agricultural University, Kampus IPB Darmaga, Bogor 16680, Indonesia

ta (SOMOGYI *et al.*, 2006). If tree-wise data are available, allometric models provide a convenient way to estimate tree biomass based on tree diameter at breast height (DBH) and or tree height. Many studies have developed general or site-specific allometric models for various species around the world. For example, PURWANTO and SHIBA (2005) developed allometric models for estimating teak tree biomass in East Java, Indonesia, using tree diameter and height as predictors. Meanwhile, KARMACHARYA and SINGH (1992), KRAENZEL *et al.* (2003), and CORDERO and KANNINEN (2003) developed allometric models for teak in India, Panama, and Costa Rica, respectively, using only tree diameter as a predictor. Such allometric models are reliable and useful tools for estimating forest biomass through aggregating individual trees biomass. However, allometric models are difficult to apply if tree-wise data are not available (JALKANEN *et al.*, 2005; SOMOGYI *et al.*, 2006), such as when forest inventories are based primarily on remotely sensed data that cannot provide accurate information on the diameter or height of individual trees.

When only stand-wise data are available, forest biomass can be estimated using stand-level biomass models. This situation is often encountered in strategic forest planning for which tree-wise data from a detailed forest inventory have been summed up into stand-wise or compartment-wise data. Several studies have developed volume-to-biomass models (e.g., LEHTONEN *et al.*, 2004; PAN *et al.*, 2004; SCHROEDER *et al.*, 1997), which can be used to directly convert stand volume into stand biomass. Despite the popularity of volume-to-biomass models, other options using different stand attributes are available for developing stand-level biomass models (SOMOGYI *et al.*, 2006); these alternatives are useful when stand volume data are difficult to obtain. For example, in simulations of the future dynamics of forest biomass or carbon stock, the age-class distribution of plantation forests is more easily obtained than stand volume. To our knowledge, relatively few studies have attempted to develop alternative biomass models as complements to volume-to-biomass models, especially those applicable to estimating stand biomass at the FMU level.

Although many studies have developed allometric models for estimating the biomass of teak trees (CORDERO and KANNINEN, 2003; KARMACHARYA and SINGH, 1992; KRAENZEL *et al.*, 2003; PURWANTO and SHIBA, 2005), little research has focused on the development of stand-level biomass models for teak plantations. Therefore, our objective was to develop stand-level biomass models for teak plantations in Central Java, Indonesia, to support multipurpose forest management at the FMU level. In addition to developing volume-to-biomass models, we were also interested in developing biomass models from other easily measured stand variables (i.e., basal area and age) to facilitate the estimation of forest biomass with minimum input data, as is often encountered in strategic forest planning.

MATERIAL AND METHODS

Study Area

This study was conducted in Balo, a forest division of the Kebonharjo FMU, located in Central Java, Indonesia (6°47′20″–6°51′22″ S, 111°32′57″–111°40′29″ E; Fig. 1). The total area of Balo is 5,448.5 ha, of which 87.1% of the area is allocated for teak

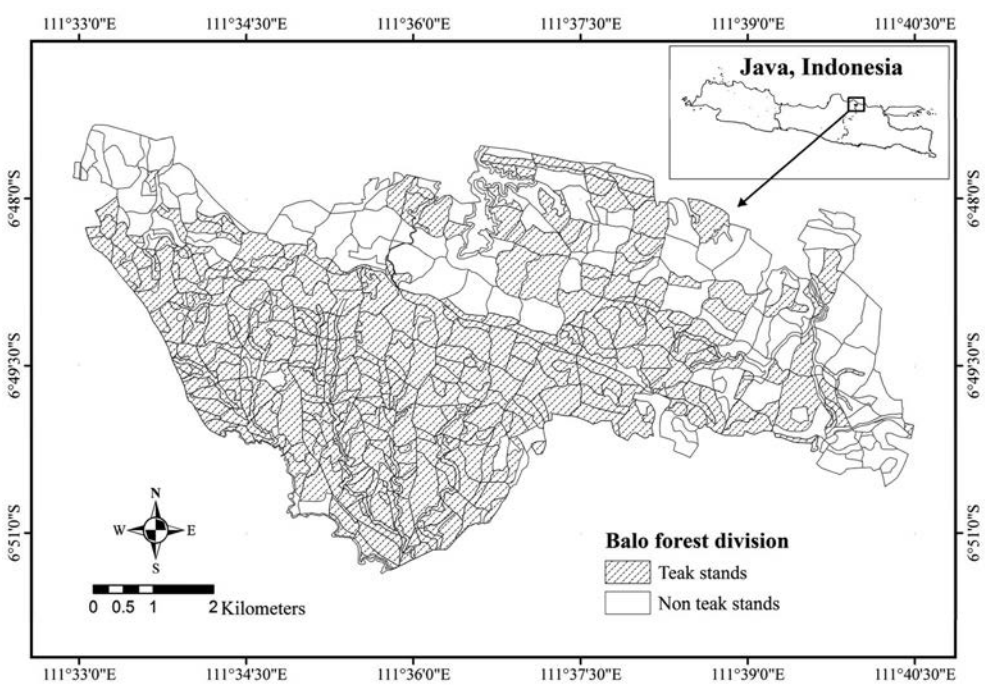

Fig. 1 Teak plantations in Balo, Kebonharjo FMU, Central Java

plantations. The teak stands are divided into 168 compartments and 495 homogenous sub-compartments with areas ranging from 0.4 to 53.0 ha (PERUM PERHUTANI, 2007; Fig. 1). The study area experiences a 5-month dry season (May–September) with mean annual rainfall (during the period 2002–2005) of 720–1,155 mm (PERUM PERHUTANI, 2007), which provides favorable conditions for teak plantations (Kaosa-ard, 1981 as cited by KRISHNAPILLAY, 2000). The plantations are managed by Perum Perhutani (PP, a state owned forestry enterprise) to produce high-quality teak timbers for building materials, furniture, and other purposes. Harvesting is conducted using a clear-cutting system starting at age 70 years, followed by artificial regeneration.

Data Collection and Preparation

This study used temporary sample plot data obtained from a forest inventory conducted by PP in the Balo forest division (PERUM PERHUTANI, 2006b). The forest inventory was conducted using stratified systematic sampling with a random start technique (see SHIVER and BORDERS, 1996; VRIES, 1986), in which approximately 2.5% of the teak stands in each forest compartment was sampled systematically at intervals of approximately 200 m. The sample plots varied in size according to stand age: 0.02 ha for stand ages of 1–20 years, 0.04 ha for stand ages of 21–40 years, and 0.10 ha for stand ages of ≥ 41 years (PERUM PERHUTANI, 1974).

A total of 755 sample plots containing 9,450 trees was used to develop stand-level biomass models (Table 1). Each sample plot contained tree measurement data: diameter at 1.3 m above ground (DBH), top height (average height of the 100 tallest trees per hectare that were measured by PP in the field using Haga hypsometer), number of trees, stand age, and other stand attributes. We then calculated basal area and volume (using a local volume table applied in the FMU) of the sample trees in each plot. Total aboveground biomass (consisting of stem, stump, branches, twigs and leaves) of the sample trees (w, kg) was determined based on DBH (d, cm) using the following allometric equation:

$$w = 0.2759 d^{2.2227} \quad (R^2 = 0.941) \tag{1}$$

This equation was derived from teak biomass data measured by HENDRI (2001) in Cepu, a neighboring FMU of the study area. HENDRI (2001) conducted a destructive sampling of 24 sample trees with DBH ranging from 6 to 75 cm (and ages ranging from 2 to 86 years). This allometric equation is applicable to the teak plantations in the study area, because the stands and climate conditions at the two FMUs are similar to each other. Moreover, no local allometric equations were available for the study area. We did not use allometric equations developed by PURWANTO and SHIBA (2005) because their equations require tree height data, which were not available for all trees in each sample plot of our data sets. In addition, their study site conditions were likely much different than those of our study site.

The tree-level data were then aggregated for each sample plot to derive the following stand variables (Table 1): biomass (W, tons/ha), age (A, years), top height (H_o, m), site index (S, m), quadratic mean diameter (Dq, cm), basal area (G, m^2/ha), number of trees (N, trees/ha) and volume (V, m^3/ha). The site index was determined using the following equation (BUDIANTHO, 1986):

$$\ln S = (\ln H_o - 6.0375)(A/80)^{0.1435} + 6.0375 \tag{2}$$

To validate the models, we also measured 39 sample plots (containing 571 trees) by conducting a field survey in some parts of the study area (Table 1). The sample plots were located subjectively in representative parts of the teak stands in compartments, independent of those measured by PP.

Model Development

The main focus of this study was to develop models that are applicable for the strategic multipurpose planning of teak plantations; hence, the models should be as simple as possible with minimum input data. Therefore, we considered only

Table 1 Summary statistics of the sample plots used for model fitting and validation

Variable	Fit data set (n = 755)				Validation data set (n = 39)			
	Mean	SD	Min	Max	Mean	SD	Min	Max
W	108.17	55.46	6.35	290.05	116.83	53.31	7.25	255.2
A	37	23	5	83	43	24	5	82
H	22.9	7.7	5	40.0	19.6	5.8	6.5	27.8
S	33.2	4.2	20.0	45.0	27.0	4.1	19.0	35.0
Dq	29.8	16.5	5.3	75.2	31.9	15.7	5.4	67.3
G	14.32	6.23	1.19	33.41	15.21	5.84	1.38	28.43
N	399	344	20	1,700	354	326	60	1,050
V	142.34	67.75	9.73	359.71	152.64	64.56	11.21	311.91

W, biomass (tons/ha); A, age (years); H, top height (m); S, site index (m); Dq, quadratic mean diameter (cm); G, basal area (m^2/ha); N, total number of trees (trees/ha); V, volume (m^3/ha); SD, standard deviation.

Table 2 Pearson's correlation coefficients among the stand variables

	A	*H*	*S*	*Dq*	*G*	*N*	*V*
H	0.90**						
S	0.05ns	0.43**					
Dq	0.93**	0.93**	0.25**				
G	0.43**	0.60**	0.51**	0.55**			
N	−0.81**	−0.76**	0.02ns	−0.80**	−0.17**		
V	0.53**	0.68**	0.48**	0.65**	0.99**	−0.29**	
W	0.59**	0.72**	0.46**	0.70**	0.97**	−0.35**	0.99**

** Significant at $P < 0.01$; ns Not significant at $P < 0.05$.

stand volume, basal area, and stand age as predictors for stand biomass. Our preliminary analysis (Table 2) indicated that stand biomass exhibited strong linear correlations (as indicated by Pearson's correlation coefficients, r) with stand volume (r = 0.99, P < 0.01), basal area (r = 0.97, P < 0.01), and stand age (r = 0.59, P < 0.01), suggesting that these stand variables were appropriate for use in the models.

We first developed volume-to-biomass (VW) models. Several studies (e.g., Lehtonen *et al.*, 2004; Pan *et al.*, 2004; Schroeder *et al.*, 1997) have indicated that the relationship between stand volume and biomass follows linear or nonlinear trends. Thus, we developed volume-to-biomass models for the teak plantations using the following simple linear and power functions (Fang *et al.*, 1998; Husch *et al.*, 2003; Lehtonen *et al.*, 2004; Pan *et al.*, 2004):

$$\text{VW1: } W = b_0 + b_1 V \quad (3a)$$
$$\text{VW2: } W = b_0 V^{b_1} \quad (3b)$$

As previously defined, W is stand biomass (tons/ha), V is stand volume (m^3/ha), and b_0 and b_1 are model parameters.

We next developed biomass models based on stand basal area. Similar to the volume-to-biomass models, the relationship between basal area and stand biomass (GW) was formulated using simple linear and power functions (adapted from Husch *et al.*, 2003; Vélez and Valle, 2007):

$$\text{GW1: } W = b_0 + b_1 G \quad (4a)$$
$$\text{GW2: } W = b_0 G^{b_1} \quad (4b)$$

Researchers often wish to estimate temporal trends of stand biomass, when, for example, only age distribution data are available. Therefore, we developed age-to-biomass models based on the temporary sample plot data as an alternative for situations when permanent sample plot data are lacking. All data from the 755 sample plots were first used to develop a global biomass model that was applicable to various sites of the teak plantations. To account for the possibility of high variability in stand biomass, we then classified the sample plots into three site groups according to their site indices: poor sites ($20 \leq S \leq 30$, equivalent to site class 1.0–2.5), intermediate sites ($31 \leq S \leq 36$, equivalent to site class 3.0–3.5), and good sites ($37 \leq S \leq 47$, equivalent to site class 4.0–6.0). Because the relationship between stand age and biomass (AW) was nonlinear, we used logarithmic (AW1), inverse polynomial (AW2), Schumacher (AW3), and negative exponential (AW4) models (adapted from Clutter *et al.*, 1988; Gadow and Hui, 1999; Pan *et al.*, 2004):

$$\text{AW1: } W = b_0 + b_1 \ln(A) \quad (5a)$$
$$\text{AW2: } W = A/(b_0 + b_1 A) \quad (5b)$$
$$\text{AW3: } W = b_0(\exp(b_1/A)) \quad (5c)$$
$$\text{AW4: } W = b_0(1-\exp(-A/b_1)) \quad (5d)$$

We also tested several complex growth models, e.g. Gompertz, logistics, and Chapman-Richards, but these theoretical models did not work well with non-sigmoidal data sets.

The fourth type of biomass model used stand age and basal area as predictors to provide alternative models for predicting stand biomass when stand age or basal area alone are less accurate. We formulated the age and basal area-to-biomass (AGW) models using the following multiple linear and logarithmic functions (Clutter *et al.*, 1988):

$$\text{AGW1: } W = b_0 + b_1 A + b_2 G \quad (6a)$$
$$\text{AGW2: } W = b_0 A^{b_1} G^{b_2} \quad (6b)$$

Similar to b_0 and b_1 in the previous equations, b_2 is also a model parameter.

All models parameters (b_0, b_1, and b_2) were estimated using generalized linear and nonlinear least squares (GLS/GNLS) methods (Draper and Smith, 1998; Pinheiro and Bates, 2000). Compared to the ordinary least squares (OLS) method, GLS/GNLS provides an effective way to eliminate the heteroscedasticity (non-constant variance) of residuals. The variance of the residuals was modeled using power functions of stand volume (for VW models), basal area (for GW and AGW models), and stand age (for AW models) to provide appropriate weights for the regression models. All statistical analyses were performed using the nlme package of R version 2.9.0 (Pinheiro and Bates, 2000; R Development Core Team, 2009).

Model Evaluation

To recommend appropriate models for estimating teak stand biomass, we assessed the performance of the four types

of biomass models using two steps. In the first step, the models were evaluated using the fit data set (Table 1) by comparing their goodness-of-fit statistics: root mean squared error (*RMSE*), Akaike's Information Criterion (*AIC*), Bayesian Information Criterion (*BIC*), and adjusted coefficient of determination (R^2_{adj}). These statistics were formulated as follows (DRAPER and SMITH, 1998; PINHEIRO and BATES, 2000; RAWLINGS *et al.*, 1998):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-p}} \tag{7a}$$

$$AIC = -2\log Lik + 2(p+1) \tag{7b}$$

$$BIC = -2\log Lik + (p+1)\log(n) \tag{7c}$$

$$R^2_{adj} = 1 - \frac{(n-1)\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{(n-p)\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \tag{7d}$$

where y_i, $\hat{y}_i$, $\bar{y}_i$ are the observed, predicted, and mean values of stand biomass, respectively; n is the number of observations; p is the number of model parameters; and *logLik* is the log-likelihood value of the linear or nonlinear model. The preferred biomass models were those with the lowest *AIC*, *BIC*, and *RMSE*, but the highest R^2_{adj}. In addition, we further compared a relative performance between two models by calculating the difference in *AIC* and *BIC* values. A difference of at least 10 in *AIC* and *BIC* values indicated a strong difference in the performance of two models (for other scoring criteria, see BURNHAM and ANDERSON, 2002; RAFTERY, 1995).

In the second step, the models were further validated using independent sample plot data (Table 1). We did not use a data-splitting approach because the split data sets were not independent of each other (HUANG *et al.*, 2003); hence, the validation results might not be reliable. This validation step is important for confirming that the models are sufficient (RAWLINGS *et al.*, 1998) for estimating stand biomass. In addition, there is no a guarantee that the quality of fit from regression analysis reflects the quality of prediction (HUANG *et al.*, 2003). To assess the goodness of prediction of the biomass models, we used the most frequently applied statistical criteria: mean error (*ME*), percentage error (*PE*%), mean absolute difference (*MAD*), mean square error of prediction (*MSEP*), relative error in prediction (*RE*%), and modeling efficiency (*EF*), which were formulated as follows (HUANG *et al.*, 2003; RAWLINGS *et al.*, 1998; SOARES *et al.*, 1995):

$$ME = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n} \tag{8a}$$

$$PE\% = \frac{100.\bar{e}}{\sum_{i=1}^{n} y_i / n} \tag{8b}$$

$$MAD = \frac{\sum_{i=1}^{n}|y_i - \hat{y}_i|}{n} \tag{8c}$$

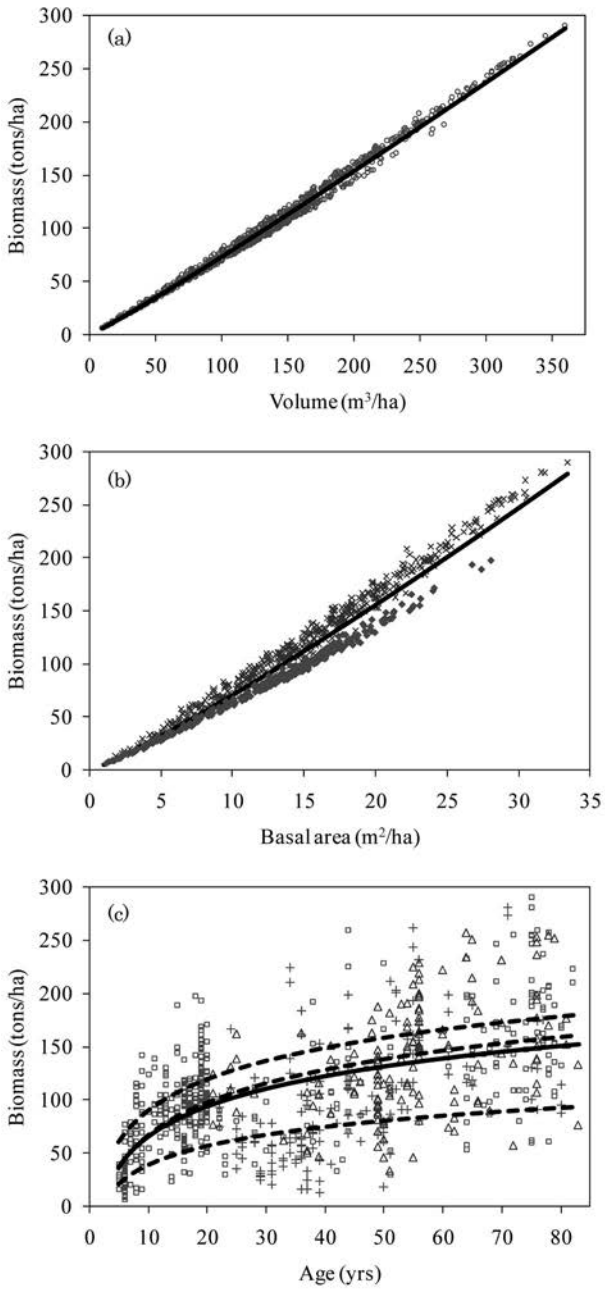

Fig. 2 Observed values of teak stand biomass plotted against (a) volume, (b) basal area, and (c) age, which are overlaid with fitted curves

Circles (o) indicate the observed values in the relationships of the volume to biomass and basal area to biomass. Diamonds (◆) and crosses (×) indicate the observed values of young and mature stands, respectively, in the relationships of the basal area to biomass. Pluses (+), squares (□), and triangles (△) indicate the observed values of the poor, intermediate, and good sites, respectively. The solid line represents the fitted curve for the all-site group (model AW1as), whereas the lower, middle, and upper dashed lines indicate the fitted curves for the poor- (model AW1ps), intermediate- (model AW1is) and good-site (model AW1gs) groups, respectively.

$$MSEP = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n} \quad (8d)$$

$$RE\% = \frac{100\sqrt{MSEP}}{\bar{y}} \quad (8e)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \quad (8f)$$

While the first three statistics (*ME*, *PE*% and *MAD*) measure the bias or accuracy of the predictions, the remainder (*MSEP*, *RE*%, and *EF*) measure the precision of the predictions (HUANG *et al.*, 2003). In addition to the goodness-of-fit statistics, the models with lower bias and higher precision were recommended for predicting stand biomass of teak plantations.

RESULTS

Volume-to-Biomass and Basal Area-to-Biomass Models

The stand volume and biomass of the teak plantations formed a nearly perfect linear relationship (r = 0.99, Table 2). There was, however, more variation in stand biomass when

Table 3 Parameter estimates, standard errors (*SE*), and related goodness-of-fit statistics of the volume-to-biomass (VW), basal area-to-biomass (GW), and age and basal area-to-biomass (AGW) models for teak plantations

Model	Parameter		*SE*	*P*-value	*RMSE*	*AIC*	*BIC*	R^2_{adj}
Volume to biomass								
VW1	b_0	−2.537	0.1647	<0.0001	5.75	4,445.72	4,464.22	0.989
	b_1	0.773	0.0020	<0.0001				
VW2	b_0	0.539	0.0083	<0.0001	4.61	4,257.93	4,276.44	0.993
	b_1	1.067	0.0031	<0.0001				
Basal area to biomass								
GW1	b_0	−5.264	0.3896	<0.0001	13.52	5,738.12	5,756.62	0.941
	b_1	7.827	0.0477	<0.0001				
GW2	b_0	5.140	0.1108	<0.0001	11.82	5,632.24	5,650.75	0.955
	b_1	1.138	0.0081	<0.0001				
Age and basal area to biomass								
AGW1	b_0	−22.110	0.6199	<0.0001	6.71	5,033.88	5,056.99	0.985
	b_1	0.492	0.0117	<0.0001				
	b_2	7.842	0.0433	<0.0001				
AGW2	b_0	3.871	0.0404	<0.0001	4.36	4,208.29	4,231.42	0.994
	b_1	0.152	0.0023	<0.0001				
	b_2	1.048	0.0037	<0.0001				

Table 4 Validation statistics of the volume-to-biomass (VW), basal area-to-biomass (GW), age-to-biomass (for all sites group, AWas), and age and basal area-to-biomass (AGW) models

Model	*ME*	*PE*%	*MAD*	*MSEP*	*RE*%	*EF*
Volume to biomass						
VW1	1.377	1.178	4.636	30.481	4.726	0.989
VW2	0.833	0.713	3.535	18.140	3.645	0.993
Basal area to biomass						
GW1	3.090	2.644	11.041	169.667	11.149	0.939
GW2	1.674	1.433	9.166	119.415	9.353	0.957
Age to biomass for all-sites group						
AW1as	0.769	0.658	29.969	1,519.760	33.368	0.451
AW2as	5.118	4.381	30.562	1,615.580	34.403	0.417
AW3as	4.639	3.971	30.866	1,686.788	35.153	0.391
AW4as	3.883	3.323	30.959	1,689.401	35.181	0.390
Age and basal area to biomass						
AGW1	−1.663	−1.423	4.969	45.141	5.751	0.984
AGW2	−2.183	−1.868	3.523	19.670	3.796	0.993

stand volume increased from about 125 to 270 m^3/ha (Fig. 2a). Both the simple linear (VW1) and the power (VW2) functions fit the data well (Table 3). All model parameters were highly significant ($P < 0.01$), and the models accounted for 99% of the total variation in stand biomass. The lower values of *AIC* and *BIC* for model VW2 indicated that this model was better than model VW1 (Table 3). Model VW2 also produced lower *RMSE* and standard errors (*SE*) of the parameters compared to model VW1, indicating that model VW2 produced more precise estimates of stand biomass.

The validation statistics (Table 4) indicated that models VW1 and VW2 produced relatively low positive biases (*ME* < 1.4 tons/ha, *PE*% < 1.2%, *MAD* < 5 tons/ha) with high precision (*MSEP* < 31, *RE*% < 5, *EF* > 0.98). But, the predictive performance of model VW2 was superior to that of model VW1. These validation results confirmed that model VW2 was appropriate for predicting stand biomass based on the stand volume of teak plantations (Fig. 2a).

Similar results were observed for the basal area-to-biomass (GW) models. Basal area and biomass exhibited a strong positive linear correlation (r = 0.97, Table 2). The variation in biomass was more pronounced with basal areas ranging from approximately 7 to 28 m^2/ha (Fig. 2b). Although the relationship between basal area and biomass revealed two distin-

Table 5 Parameter estimates, standard errors (*SE*), and related goodness-of-fit statistics of the age-to-biomass (AW) models for teak plantations

Model	Estimates		*SE*	*P*-value	*RMSE*	*AIC*	*BIC*	R^2_{adj}
All sites (as):								
AW1as	b_0	−28.734	5.2241	<0.0001	45.18	7,794.64	7,813.14	0.336
	b_1	40.887	1.7494	<0.0001				
AW2as	b_0	0.095	0.0059	<0.0001	45.74	7,815.01	7,833.52	0.319
	b_1	0.006	0.0002	<0.0001				
AW3as	b_0	148.182	3.6385	<0.0001	46.47	7,807.99	7,826.50	0.298
	b_1	−7.831	0.4163	<0.0001				
AW4as	b_0	134.845	3.6488	<0.0001	46.89	7,835.04	7,853.54	0.285
	b_1	15.437	0.9885	<0.0001				
Poor sites (ps):								
AW1ps	b_0	−20.343	6.5593	0.0023	28.45	1,457.65	1,469.77	0.329
	b_1	25.648	2.3867	<0.0001				
AW2ps	b_0	0.167	0.0247	<0.0001	28.75	1,466.64	1,478.81	0.316
	b_1	0.009	0.0010	<0.0001				
AW3ps	b_0	87.791	5.1580	<0.0001	29.00	1,463.63	1,475.80	0.303
	b_1	−7.586	0.8473	<0.0001				
AW4ps	b_0	77.489	5.6744	<0.0001	29.39	1,468.09	1,480.26	0.285
	b_1	14.282	2.4186	<0.0001				
Intermediate sites (is):								
AW1is	b_0	−34.964	6.0212	<0.0001	42.56	4,639.38	4,655.87	0.359
	b_1	44.299	1.9952	<0.0001				
AW2is	b_0	0.095	0.0062	<0.0001	42.89	4,652.24	4,668.74	0.349
	b_1	0.005	0.0002	<0.0001				
AW3is	b_0	160.806	4.2967	<0.0001	43.37	4,643.94	4,660.44	0.334
	b_1	−8.668	0.4910	<0.0001				
AW4is	b_0	146.056	4.2365	<0.0001	43.64	4,657.30	4,673.80	0.326
	b_1	16.805	1.1142	<0.0001				
Good site (gs):								
AW1gs	b_0	−7.100	10.522	0.5009	39.01	1,418.49	1,430.28	0.438
	b_1	42.270	3.8386	<0.0001				
AW2gs	b_0	0.059	0.0059	<0.0001	39.83	1,430.05	1,441.89	0.414
	b_1	0.005	0.0003	<0.0001				
AW3gs	b_0	169.233	7.7921	<0.0001	40.95	1,432.92	1,444.77	0.381
	b_1	−6.055	0.5994	<0.0001				
AW4gs	b_0	154.333	7.2612	<0.0001	41.43	1,437.53	1,449.38	0.366
	b_1	11.552	1.1939	<0.0001				

guishable nearly linear trends, we only fit a general model that was applicable for both trends to provide an easy-to-use biomass model.

Both simple linear (GW1) and power (GW2) models produced highly significant parameters ($P < 0.01$, Table 3) with relatively low standard errors ($SE < 0.4$). Comparisons of the goodness-of-fit statistics from these models suggested that model GW2 outperformed model GW1, as indicated by lower values of *AIC*, *BIC*, and *RMSE* (Table 3). Model GW2 explained about 96% of the total variation in stand biomass, which was slightly higher than that of model GW1. The appropriateness of model GW2 for predicting stand biomass was also confirmed by the validation results (Table 4). All statistical criteria consistently indicated that model GW2 performed better (i.e. lower bias and higher precision) than model GW1. The model was fit to the data reasonably well by averaging the two obvious trends of stand biomass (Fig. 2b).

Age-to-Biomass Model

Stand biomass varied greatly with stand age (Fig. 2c). The high variability of stand biomass occurred not only between stands of different ages but also within stands of a certain age. In older stands, the variation in biomass was higher than in younger stands. Although we classified the plantations into three site groups (poor, intermediate, and good sites), the variation in stand biomass within each site group was still high. There was no clear separation of stand biomass among the site groups. For instance, the stand biomass of intermediate sites partially overlapped with those of poor and good sites. The site grouping was not particularly effective in reducing the high variability of stand biomass. Nevertheless, the four biomass models fit the variable age-biomass data reasonably well (Table 5).

For the all-sites group, model AW1as performed better than the other three models, based on slightly lower *AIC*, *BIC*, and *RMSE* values (Table 5). This model, however, only explained about 34% of the total variation in stand biomass, which was slightly higher than the other AW models. Further assessment using the validation data set indicated that model AW1as produced lower positive bias ($PE\% = 0.66\%$, $MAD = 29.6$ tons/ha) and slightly more precision ($RE\% = 33.4\%$, $EF = 0.451$) than the other models. Thus, model AW1as was an appropriate global model for estimating stand biomass at the various teak plantation sites (Fig. 2c).

When we modeled stand biomass for each site group, the goodness-of-fits of the specific models improved slightly (Table 5). Except for parameter b_0 of model AW1gs, all model parameters were highly significant ($P < 0.01$). Compared to the global model (AW1as), the specific models reduced the *RMSE* to about 3–37% and increased R^2_{adj} to about 15–30%. Similar to the global model, model AW1 for each site group was consistently better than the others, as indicated by the goodness-of-fit statistics. Unfortunately, because of the limited number of sample plots in the validation data set, we could not further validate the specific models for each site group using independent data sets. Nevertheless, these results suggested that the AW1 (logarithmic) models were appropriate for predicting stand biomass based on stand age (Fig. 2c).

Age and Basal Area-to-Biomass Model

The poor performance of the age-to-biomass models indicated that stand age alone could not satisfactorily explain the high variation in stand biomass. Therefore, we included basal area as an additional independent variable in the models to provide alternatives to the less accurate age-to-biomass and basal area-to-biomass models. We did not use the site index as an independent variable because it was more weakly correlated with stand biomass ($r = 0.46$, Table 2) and was an inherently biased variable estimated from stand age and top height.

Both the multiple linear (AGW1) and logarithmic (AGW2) models fit the data well (Table 3). All parameters were highly significant ($P < 0.01$), and the models explained more than 98% of the total variation in stand biomass. Model AGW2, however, was superior to model AGW1 because it produced lower *AIC*, *BIC*, and *RMSE* with slightly higher R^2_{adj}. The validation results (Table 4) also confirmed that model AGW2 produced more accurate (lower bias) and precise estimates of stand biomass compared to model AGW1.

Model AGW2 also outperformed the basal area-to-biomass (GW2) and age-to-biomass (AW1) models, as indicated by the goodness-of-fit statistics (Table 3). Whereas model AGW2 only reduced *RMSE* up to 63% compared to model GW2, it drastically reduced *RMSE* up to 90% compared to model AW1as. The *AIC* and *BIC* values of model AGW2 were also lower than those of model GW2 and AW1as. In addition, the large difference in *AIC*/*BIC* values between model GW2 and AGW2 (i.e. 1424 values) and between model AW1as and AGW2 (i.e. 3586 values) confirmed the superior performance of model AGW2. These results indicated that the inclusion of stand age and basal area in the models produced more accurate and precise estimates of stand biomass.

DISCUSSION

The development of stand level biomass models has gained much attention (e.g., Fang *et al.*, 1998; Lehtonen *et al.*, 2004; Pan *et al.*, 2004; Schroeder *et al.*, 1997) for their use in facilitating the estimation of forest biomass at the stand, regional, or national level, especially when tree-wise data are not available. Previous studies have demonstrated that the relationship between stand volume and biomass can be formulated using simple functions, such as linear (Fang *et al.*, 1998), power (Lehtonen *et al.*, 2004; Pan *et al.*, 2004), and polynomial functions (Schroeder *et al.*, 1997). Our study confirmed that a simple power function (model VW2) is also appropriate for

estimating the stand biomass of teak plantations based on stand volume data. Despite differences in forest species and underlying functions used in volume-to-biomass models, stand biomass was consistently strongly correlated with stand volume. The slight variation in teak stand biomass (Fig. 2a) can be attributed to differences in stand volume in young (≤20 years old) and mature stands (>20 years old). PAN *et al.* (2004) also observed that the relationship between stand biomass and volume is affected by variation in stand age. Our results, however, indicated that the variation in volume-biomass relationships in young and mature stands did not differ greatly; hence, it was unnecessary to develop two separate models.

One advantage of the volume-to-biomass model is that it provides a direct conversion of stand volume to stand biomass without the use of biomass expansion factors (PAN *et al.*, 2004; SOMOGYI *et al.*, 2006). Our volume-to-biomass model (VW2) is applicable for teak plantations whose stand volumes range from 10 to 360 m^3/ha (Table 1). This range is wide enough to cover most of the variation in standing stock volume of teak plantations at various sites in Central Java, as it covers about 73% of the volume range (10.1–487.2 m^3/ha) in the existing normal yield table (WULFING, 1938). Users should be aware, however, that a volume-to-biomass model may contain an inherent bias, because stand volume is usually estimated from other stand variables (e.g. basal area and mean height) using stand volume equations (HUSCH *et al.*, 2003). We were unable to confirm this supposition in this study; thus, further investigations are necessary.

The variation in teak stand biomass was strongly affected by variation in basal area (Fig. 2b). This finding was consistent with the fact that basal area, which is well recognized as a good measure of stand density, is directly related to stand biomass (HUSCH *et al.*, 2003). Many studies have also shown that variation in basal area is the primary cause of variation in stand yield (SKOVSGAARD and VANCLAY, 2008), including stand biomass. The two distinguishable nearly linear trends (Fig. 2b) can be attributed to differences in basal area between young and mature stands, resulting from variation in the number of trees and quadratic mean diameters (Fig. 3). Variability in the number of trees can be caused by partial thinning and stand damage. During our field work, we observed that thinning was partially implemented because of budget constraints as well as the fact that young teak trees are less profitable. The unthinned stands appeared to have greater biomass than thinned stands (see also ERIKSSON, 2006). In addition, stand damage caused by illegal logging, land encroachment, forest fire, and/or grazing negatively affects the productivity of teak plantations. Although young stands have higher numbers of trees compared to mature stands, their diameters and basal areas are smaller; thus, they contain less biomass (as indicated by the lower nearly linear trend in Fig. 2b).

The basal area-to-biomass model (GW2) provides an alternative for estimating stand biomass using basal area data, although its performance was lower than that of model VW2: R^2_{adj} decreased by 3.8% and the large difference in *AIC*/*BIC* values (i.e. 1374) suggested a strong difference in the performance of both models. This weaker performance can be attributed to the fact that the relationship between basal area and stand biomass was more variable than that of volume and biomass; thus, model GW2 provided a slightly weaker fit to the data. The appropriateness of a simple power function to relate basal area to stand biomass was also confirmed by VÉLEZ and VALLE (2007) for *Acacia mangium* plantations. Model GW2 offers an advantage because it only uses basal area, which is easier to measure than volume. In the field, instead of measuring tree DBH, stand basal area can be measured using the horizontal point sampling technique (HUSCH *et al.*, 2003), which enables a rapid estimation of stand biomass. For a large-scale forest area, stand biomass can be estimated from basal area data derived from radar data (HUSSIN *et al.*, 1991) or other remotely sensed data. Our model (GW2) can be used to estimate teak stand biomass with input of basal areas ranging from 1.2 to 33.4 m^2/ha (Table 1), which covers almost all of the variation in basal area in the existing normal yield table of teak plantations (WULFING, 1938).

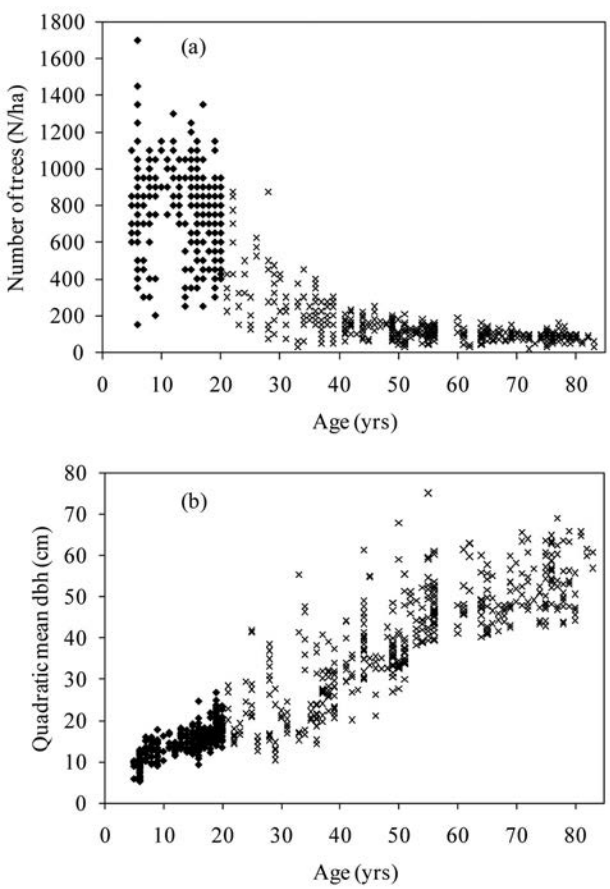

Fig. 3 The relationship between age and (a) number of trees per hectare and (b) quadratic mean diameters in young (◆) and mature (×) stands of teak plantations

Unlike the volume-to-biomass model (VW1) or the basal area-to-biomass model (GW2), the age-to-biomass models (AW1) exhibited poor performance, indicating that stand age alone cannot adequately explain variation in stand biomass. Differences in the number of trees and mean DBH, even within a certain stand age (Fig. 3b), were possible causes of the high variation in stand biomass. CORDERO and KANNINEN (2003) also confirmed that teak stand biomass in Costa Rica was influenced by variability in the number of trees. However, for mature stands, the higher variation in biomass appeared to correspond to higher variability in mean DBH (Fig. 3b). Because we used data from temporary sample plots that cover various sites, such high variation was inevitable due to differences in thinning treatments, soil conditions, and stand disturbances.

Unexpectedly, site grouping was minimally effective in reducing variability in stand biomass. This finding indicated that the site index, which was estimated from the relationship between stand age and top height, may not be a consistently reliable indicator for site productivity in term of forest biomass. Similarly, Wiant and Fountain (1980) confirmed that the site index was a poor predictor of oak biomass yields. In our case, teak stand biomass was more strongly affected by differences in stand density (either number of trees or basal area) than by variability in the site index, which is generally considered to be less affected by stand density (HUSCH *et al.*, 2003; SKOVSGAARD and VANCLAY, 2008). Therefore, teak stands with similar site indices may have different stand biomasses as the result of variability in stand densities. The weak relationship between site index and teak stand biomass can also be attributed to inherent biases in estimating these stand variables. The allometric equation (Eq. 1) used to estimate tree biomass, which only depends on DBH, may have generated some bias in estimating actual stand biomass, as it ignores variation in stand height, which can contribute to variability in stand biomass under various site conditions. Clearly, stand height (in terms of top height) is a key variable for determining the site index of teak stands (Eq. 2). In contrast, the site index equation may produce less accurate estimates of site productivity. While we could not find relevant studies for teak plantations in Java, inaccurate predictions of the site index equation were also reported by MALENDE and TEMU (1990) for teak plantations in Tanzania. These authors suggested that another set of site index equations should be used after stands reach about two-thirds of the rotation age. Similarly, site indices of teak plantations in Trinidad also decreased with increasing stand age (LAMB, 1957 as cited by MALENDE and TEMU, 1990).

Despite high variability in the relationship between stand age and biomass, the selected age-to-biomass models (AW1as, AW1bs, AW1ms, and AW1gs) clearly illustrate the increments of stand biomass with increasing stand age (Fig. 2c). Similar to our results, CORDERO and KANNINEN (2003) confirmed that teak stand biomass in Costa Rica increased from young to mature stands, whereas KARMACHARYA and SINGH (1992) reported that teak stand biomass in India was three times higher at 30 years than at 4 years. Despite their poor performance, the age-to-biomass models provide an advantage over the other models, because age-distribution data of plantation forests are typically easier to obtain than basal area or volume data. Our models can be used to estimate teak stand biomass whose ages range from 5 to 83 years (Table 1), which covers most of the variation in age of teak plantations in Java. When information on site class is not available, the global age-to-biomass model (AW1as) is appropriate for estimating stand biomass. For example, the estimates of teak stand biomass at 14 and 30 years old are 79.2 and 110.3 tons/ha, respectively, which are much higher than those of teak plantations of the same ages in India (i.e., 39.9 and 79.9 tons/ha; KARMACHARYA and SINGH, 1992). These differences are reasonable because forest biomass tends to vary according to local site, climate, and stand conditions.

The performance of stand age and basal area as predictors of stand biomass (model AGW2) was comparable to that of the volume-to-biomass model (VW2). This result suggests that model AGW2 can be used as an alternative for estimating teak stand biomass in lieu of model GW2 or models AW1. Stand age and basal area data are usually easier to obtain; hence, model AGW2 provides a practical tool for estimating teak stand biomass.

The four types of biomass models (VW2, AGW2, GW2, and AW1) developed in this study can be used to support the multipurpose management of teak plantations in the study area or similar areas in Java. The models use input data that can be easily supplied from existing forest inventories. Because our data were limited, we could not further validate the appropriateness of the proposed models for other regions. Therefore, we advise against the use of the models for regions whose stand and site conditions differ greatly from the study area. Nevertheless, similar models can be developed for other regions to obtain more comprehensive stand-level biomass models that cover the entire range of variation in teak plantations in Java.

CONCLUSIONS

This study developed four types of models for predicting the stand biomass of teak plantations based on stand variables that can be derived from existing forest inventory data. The volume-to-biomass model (VW2) produced the most accurate and precise estimates of stand biomass. The age and basal area-to-biomass model (AGW2) is more appropriate than the basal area-to-biomass model (GW2) for estimating stand biomass, as its performance was comparable to that of the volume-to-biomass model. When only age-distribution data are available, stand biomass can be estimated by the age-to-biomass model (AW1), using either the global model or the specific models, depending on the availability of site-class da-

ta. The age-to-biomass models, however, were less accurate compared to the other models. These four types of biomass models will serve as valuable tools for supporting the multi-purpose management of teak plantations in Java.

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Article

Estimating Carbon Sequestration by Sugi (*Cryptomeria japonica*) Plantations According to Site and Management Conditions

Yoko Asada[*1, 2] and Satoshi Tatsuhara[*1]

ABSTRACT

Carbon sequestration by plantation forests depends on the site conditions and silvicultural system used. This study estimated the spatial distribution of carbon sequestration by sugi (*Cryptomeria japonica*) plantations in a study area according to site quality and thinning regime. The study area was the University of Tokyo Forest in Chiba, which is located on the southern Boso Peninsula, Japan. Site index curves were created from height measurements in sugi plantation experimental plots. Sixty-five sampling points were located in sugi plantations, and the heights of three to five dominant trees around each sample point were measured. The site index was calculated for each sampling point, and the average height at 60 years of age was estimated from the average height at each sampling point using the site index curves. Site factors were calculated from a digital elevation model (DEM) in a geographic information system (GIS). Discriminant functions were developed from five site factors: slope, shaded relief, distance from a ridge, plan curvature, and the wetness index. The correctness rate was 60%. In addition, stand growth was predicted for each site quality using LYCS ver. 2.32 under low thinning at frequencies of 1, 2, 3, and 5 times. Carbon sequestration was estimated from the growth of stand volume multiplied by the basic density, biomass expansion factors, ratio of total biomass to aboveground biomass, and carbon fraction. The estimated carbon storage and sequestration for the study area were mapped using GIS according to the site quality estimated from the five site factors and specified thinning regimes. The average carbon storage per hectare peaked at a thinning frequency of one. Thinning during the young stage increased carbon storage, although frequent and strong thinning regimes decreased carbon storage. The average carbon sequestration per hectare increased with thinning frequency because more frequent thinning leads to faster growth just after thinning in more stands. These maps enabled us to understand the change in carbon storage and sequestration over the study area according to the chosen silvicultural system.

Keywords: carbon sequestration, carbon storage, plantation forests, site quality, thinning regimes

INTRODUCTION

Global climate change is a concern throughout the world. Plantation forests are expected to help mitigate global warming by serving as carbon dioxide sinks. Thus, it is important to know the extent of carbon sequestration by such forest systems. Forest growth depends on site conditions and the type of silvicultural system used. Therefore, to evaluate the amount of carbon sequestration provided by plantation forests, the site conditions and silvicultural systems, especially thinning regimes, of individual stands must be examined. Site indices can be estimated from geographic or environmental factors using a geographic information system (GIS; Iverson *et al.*, 1997; Chen and Abe, 1999; Mitsuda *et al.*, 2001; 2007). Moreover, GIS techniques play an important role in mapping the spatial distribu-

Corresponding author: Yoko Asada
E-mail: y.asada@murc.jp
[*1] Graduate School of Agricultural and Life Sciences, the University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-8657, Japan
[*2] Present address: Mitsubishi UFJ Research & Consulting Co., Ltd., Shinagawa Grand Central Tower, 2-16-4, Konan, Minato-ku, Tokyo 108-8248, Japan

tion of site quality.

Japanese cedar (sugi, *Cryptomeria japonica* D. DON) is a major plantation species throughout most areas of Japan. Sugi plantations account for approximately 43% of the extent of plantation forests in Japan. The objectives of this study were, using GIS, to estimate the spatial distribution of carbon sequestration by sugi plantations based on site quality and thinning regime. We developed a model for estimating the site quality of sugi plantations from various environmental factors. In addition, stand growth was predicted for each level of site quality under various thinning regimes to map the spatial distribution of carbon storage and carbon sequestration in sugi plantations using GIS. This case study was conducted at the Tokyo University Forest in Chiba (hereafter, Chiba Forest).

STUDY AREA

The study area comprised sugi plantation forests in Chiba Forest, which is located in the southern part of the Boso Peninsula, Japan (35°9 - 13' N, 140°6 - 10' E ; Fig. 1). Most of the plantations in the region are sugi and hinoki cypress (*Chamaecyparis obtusa* [SIEB. et ZUCC.] ENDL.). Of the approximately 2,171 ha of Chiba Forest, 476.75 ha comprise sugi plantations. The ages of the plantations range from young to over-mature, and the oldest stand is approximately 160 years old. The elevation of the study area ranges from 50 to 370 m above sea level. The topographic features are complex, and the slope is generally very steep. The underlying rock consists of sandstone, conglomerate, mud stone, and tuff. The main soil type is brown forest soil, which is distributed throughout most parts of Chiba Forest. The monthly mean temperatures in midwinter and midsummer are around 4℃ and 20℃, respectively. The annual mean temperature is about 14℃, and annual precipitation varies from 2,000 to 2,400 mm.

METHODS

Creation of a Site Index Curve from Height Measurements

In most studies, logistic, MITSCHERLICH, and GOMPERTZ functions are used as height growth curves or site index curves. These functions are useful for estimating site indices based on a key age of 40 years from average tree height at different ages. However, accurate estimates of the site index based on the average tree height of old stands are difficult to acquire, because the current site index curves were developed using data that did not include mature stands.

In this study, new site index curves that are more applicable to old stands were developed by applying data that included mature stands to select the best model results. Height measurements at eight experimental plots (TAKEUCHI and HASEGAWA, 1975; SUZUKI *et al.*, 1999) within sugi plantations were used for developing site index curves. A diameter-height curve was developed for each plot by applying the NÄSLUND formula to diameter and height measurements of sample trees. The tree heights in each plot were calculated from diameter measurements with the diameter-height curve. Average height was calculated by averaging the heights of the 100 largest (based on diameter at breast height: DBH) trees per ha (ISHIBASHI, 2006). Six functions, the MITSCHERLICH, GOMPERTZ, logistic, RICHARDS, and two logistic-type functions, were applied to age-height data:

$$H = k(1 - ab^t), \tag{1}$$

$$H = ka^{b^t}, \tag{2}$$

$$H = \frac{k}{1 + a\exp(-bt)}, \tag{3}$$

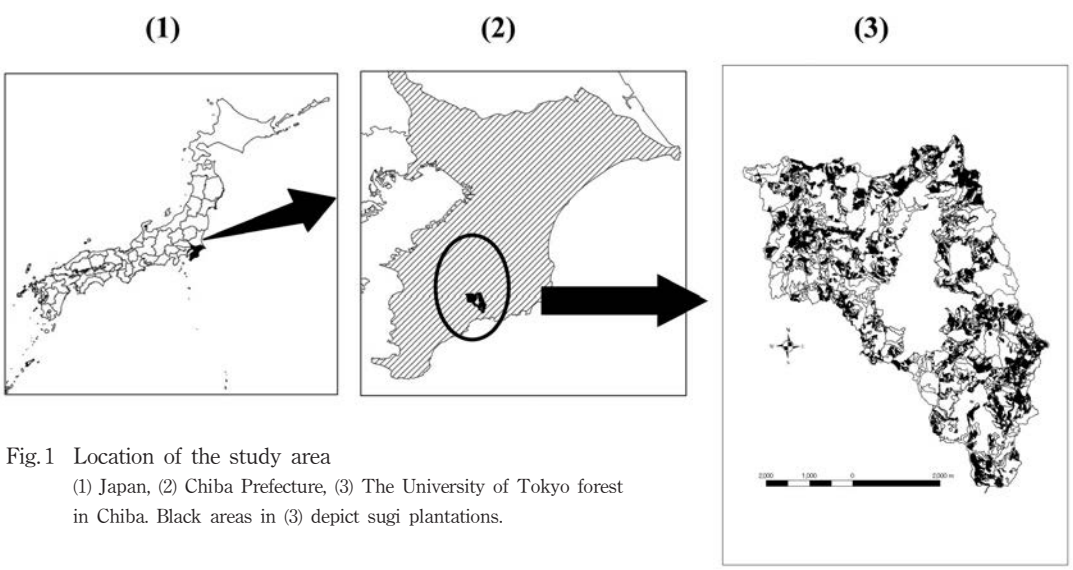

Fig. 1 Location of the study area
(1) Japan, (2) Chiba Prefecture, (3) The University of Tokyo forest in Chiba. Black areas in (3) depict sugi plantations.

$$H = k(1+\exp(at))^{\frac{1}{1-b}}, \tag{4}$$

$$H = \frac{k}{1+\exp(a+b\ln(1+t))}, \tag{5}$$

$$H = \frac{SI(1+\exp(a+b\ln(60+c)-\ln SI))}{1+\exp(a+b\ln(60+c)-\ln SI)}, \tag{6}$$

where H is dominant height, t is stand age, SI is the site index, and a, b, c, and k are parameters. Equations (5) and (6) are modified logistic functions that showed favourable performance for lodgepole pine (*Pinus contorta*) secondary forests in Alberta Province, Canada (HUANG, 1999; MENG and HUANG, 2009).

Because Equation (6) includes the site index as an independent variable, root mean square error (RMSE) and AKAIKE's information criteria (AIC) were calculated directly from the applied data, as shown in Equations (7) and (8):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\hat{x}_i)^2}{n}}, \tag{7}$$

$$\mathrm{AIC} = n\left(\ln 2\pi\frac{\sum_{i=1}^{n}(x_i-\hat{x}_i)^2}{n}+1\right)+2(p+1), \tag{8}$$

where n is the number of data, p is the number of parameters in the model, x_i is the observed value, and $\hat{x}_i$ is the estimated value. Parameters for the five other equations were obtained, and the fit equations were used as guide curves to develop site index curves. Parameter k was modified for each experimental plot, so that the value of the equations at a base age of 60 years was equal to the estimated average height at that age. The RMSE and AIC were then calculated.

Development of a Model to Estimate Site Quality

Twelve sample slopes were selected in sugi plantations to include various slope aspects. Sampling points were established about every 20 m along the slopes. As a result, 65 sampling points were located in the sugi plantations, and the heights of 3 to 5 dominant trees around each point were measured (TATSUHARA, 2008). The average height of the dominant trees at 60 years of age was calculated for each sampling point from the dominant height at each sampling point using the site index curves. Then, sampling points were classified into five site qualities, based on their height at 60 years of age according to the following classification: site quality 1, >26 m; site quality 2, 22–26 m; site quality 3, 19–22 m; site quality 4, 17–19 m; site quality 5, <17 m, based on the yield tables for sugi in Chiba Forest constructed by NAGUMO *et al.* (1981).

The GIS software ArcGIS 9.3 (ESRI) including ArcInfo Workstation 9.3 (ESRI) was used in this study. Contours were digitised from 1:5,000 orthophotographs. A digital elevation model (DEM) was created for the study area by interpolating the altitude of each grid cell from the contours and adding spot heights of mountaintops using the method of HUTCHINSON (1989). The spatial resolution of the DEM was set at 20 × 20m.

The site productivity of stands is affected by site factors such as soil properties as well as topographic and climatic features. Assuming a reasonably similar climate, elevation, disturbance history, and soil fertility among sites, variation in productivity will be driven primarily by moisture availability (IVERSON *et al.*, 1997). Topographic features, such as slope steepness, aspect, and slope position, as well as solar radiation, influence soil moisture levels. Therefore, eight environmental factors (slope, flow accumulation, three types of curvature, the wetness index, distance from a ridge, and shaded relief) were used as possible predictor variables to estimate the site index; the three types of curvature were plan curvature, profile curvature, and curvature (plan curvature - profile curvature). These factors were chosen because they were easily calculated on the basis of the DEM and GIS. The first seven variables describe hydrologic characteristics, whereas shaded relief describes the level of solar radiation.

The slope describes overland and subsurface flow velocity and runoff rate (MOORE *et al.*, 1991) and was calculated as the average of the slope angle measurements for the upper and lower side of each point, excluding edge points. In the GIS, the slope was estimated for each cell from the DEM.

Flow accumulation is a measure of the surface or shallow subsurface runoff at a given point on the landscape and integrates the effects of the upslope-contributing area and catchment convergence and divergence on runoff (MOORE *et al.*, 1991). The specific catchment area was calculated by counting the number of upstream cells for each cell in the DEM (JENSON and DOMINGUE, 1988).

The curvature represents the shape of the landscape, whether flat, convex, or concave, and was calculated for each cell from surrounding cells on the DEM. A value of zero indicates a flat surface. The more convex or concave a surface, the larger its absolute value is. ZASLAVSKY and SINAI (1981) observed that soil water content was related to curvature.

The wetness index was a compound topographic index representing soil water content and surface saturation zones (MOORE *et al.*, 1991). The index was defined as:

$$\text{Wetness index} = \ln(A/\tan\beta), \tag{9}$$

where A is flow accumulation + 1 and β is the slope angle, assuming uniform soil properties.

The shaded relief map represents the hypothetical illumination values of a surface in relation to neighbouring cells by setting a position for a hypothetical light source. Shaded relief is a relative value that varies from 0 to 255 and represents the effect of the intensity of solar radiation on the drying of soil. A solar azimuth of 202 degrees and a solar altitude of 45 degrees were used for the light position. We chose this solar azimuth because maximum drying of soil occurs on aspects

Table 1 Assessed thinning regimes

No.	Frequency	Stand age at time of thinning (years)	Strength of thinning (% of thinned trees to the total)
1	1	25	30
2	2	25,40	30,30
3	3	25,40,70	30,30,40
4	5	25,35,50,70,90	30,30,30,30,30

Table 2 Root mean square errors (RMSE) and AKAIKE's information criteria (AIC) of the applied growth functions

Growth functions	RMSE	AIC
Equation (1)	1.3978	534.15
Equation (2)	1.5572	566.54
Equation (3)	1.7948	609.14
Equation (4)	1.4879	552.90
Equation (5)	1.3734	528.88
Equation (6)	1.2364	499.34

slightly west of south (SSW) due to the added drying potential of higher afternoon temperatures (IVERSON *et al.*, 1997), although maximum cumulative solar radiation over a year occurs on steep, south-facing slopes (LEE and BAUMGARTNER, 1966). We chose this solar altitude because it approximates the growing season average (IVERSON *et al.*, 1997).

The distance from a ridge was calculated using values of flow accumulation. We inverted the DEM data and applied an ArcGIS spatial analyst "flow accumulation" function. Then, we chose several points at which the value of flow accumulation was large to represent ridges, and the distance from a ridge to a sampling point was calculated.

The locations of the 65 sampling points were imported into the GIS, and the abovementioned site factors at each sampling point were obtained from their layers. Using discriminant analysis, a discriminant function with suitable site factors was developed to estimate site quality in the study area from the site quality and site factors at the 65 sampling points.

Prediction of Carbon Storage and Sequestration by Sugi Plantations

The volume growth of sugi plantations was predicted using the stand growth prediction system LYCS ver. 2.32 (MATSUMOTO, 1997). Site index curves in LYCS were replaced with the new ones developed in this study. Density at 20 years of age was set at 3,000 trees/ha, and four thinning regimes were assessed (Table 1). The level of thinning was assumed to be low for the four regimes. In thinning regime no. 1, pre-commercial thinning was conducted at a young age, and then no operations were conducted. In thinning regime no. 2, commercial thinning was conducted in addition to the thinning in regime no. 1, after which no operations were conducted. In thinning regime no. 3, old-age commercial thinning was added to thinning regime no. 2. Thinning regime no. 4 was intensive, and thinning was conducted frequently until an old age. Carbon storage and sequestration in sugi plantations were predicted from the stand volume and its growth for each site quality and thinning regime using the following equation:

$$y = v \times b \times BEF \times r \times c, \tag{10}$$

where y is carbon weight (t), v is stand volume (m^3), b is basic density (0.314 t-dm/m^3), BEF are biomass expansion factors (1.57 at ages $\leq$ 20 years and 1.23 at ages $>$ 20 years), r is the ratio of total biomass to aboveground biomass (1.25), and c is the carbon fraction (0.5 t-C/t-dm) (GOVERNMENT OF JAPAN, 2009). The volume of dead and thinned trees was excluded from volume growth.

Mapping the Spatial Distribution of Carbon Storage and Sequestration

Site quality in the study area was estimated by the discriminant functions based on raster data using GIS. The carbon storage and sequestration distributions were mapped using GIS according to the estimated site quality and specified thinning regimes. Moreover, their average values in the Chiba Forest sugi plantations were calculated.

RESULTS

Site Index Curves

Equation (6) was chosen as the best site index function

Table 3 Discriminant functions to estimate site quality from site factors

Variable	Discriminant coefficients			
	Function 1	Function 2	Function 3	Function 4
Slope	0.0471	0.0755	−0.0575	−0.0436
Shaded relief	−0.0141	0.0038	−0.0016	0.0190
Distance from ridge	0.0623	−0.0023	0.0416	0.0423
Plan curvature	0.5314	0.3773	1.2106	−0.0370
Wetness index	0.6142	−0.4679	−0.1351	−0.3759
Constant term	−1.0595	−1.4576	0.7822	−2.2863

because it produced the smallest AIC of the six functions (Table 2). The estimated parameters of Equation (6) were as follows:

$$a = 8.285,\ b = -1.22,\ c = 16.195.$$

This function proved more suitable for old growth forests than the currently available site index curves.

Site Factors

Discriminant functions to estimate site quality were developed from five site factors: slope, shaded relief, distance from a ridge, plan curvature, and the wetness index (Table 3). The correctness rate of the discriminant functions was 60%. For each cell, site quality was mapped with GIS using the discriminant functions for the five factors (Fig. 2).

Carbon Storage and Sequestration

Comparison 1. Carbon storage under various thinning regimes

Carbon storage peaked at a thinning frequency of 1 (Figs. 3 and 4). Thinning during the young stage increased carbon storage in plantation forests, whereas strong and frequent thinning regimes decreased carbon storage.

Comparison 2. Carbon sequestration under various thinning regimes

Carbon sequestration increased with thinning frequency, because more frequent thinning led to rapid growth just after thinning in more stands (Figs. 5 and 6).

Comparison 3. Carbon storage over time

Carbon storage was simulated under the assumption that sugi stands were not replanted or cut during the simulation. Carbon storage increased over time under conditions of moderate thinning (Figs. 7 and 8).

DISCUSSION

The growth of sugi is affected not only by age and genetics but also by site conditions such as soil fertility and moisture. In other words, even at the same age, trees may grow at different rates depending on their slope positions (TAKESHITA, 1964). The method used here to estimate site quality for sugi plantations using site factors derived from DEM data can easily be applied more broadly. Thus, this approach would be helpful for evaluating future carbon sequestration.

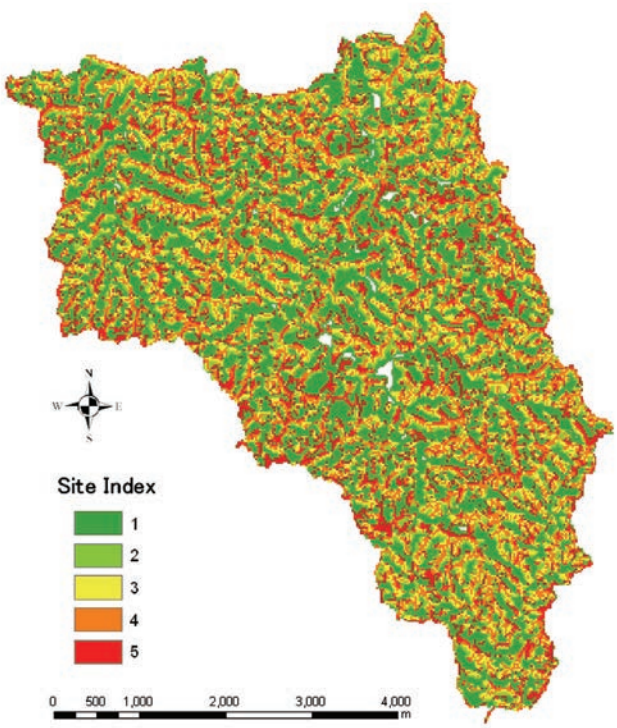

Fig. 2 Distribution of the site index estimated from site factors

The results indicated that the study area still absorbs carbon. At high quality sites, sugi stands continue to grow even after reaching maturity (NISHIZONO *et al.*, 2008). The current study area contains many sugi plantation areas of good quality. These results are consistent with the results of NISHIZONO *et al.* (2008).

The results of this study also indicated that the more frequently plantation forests were thinned, the more carbon was absorbed by the forests. Thinning can contribute to increases

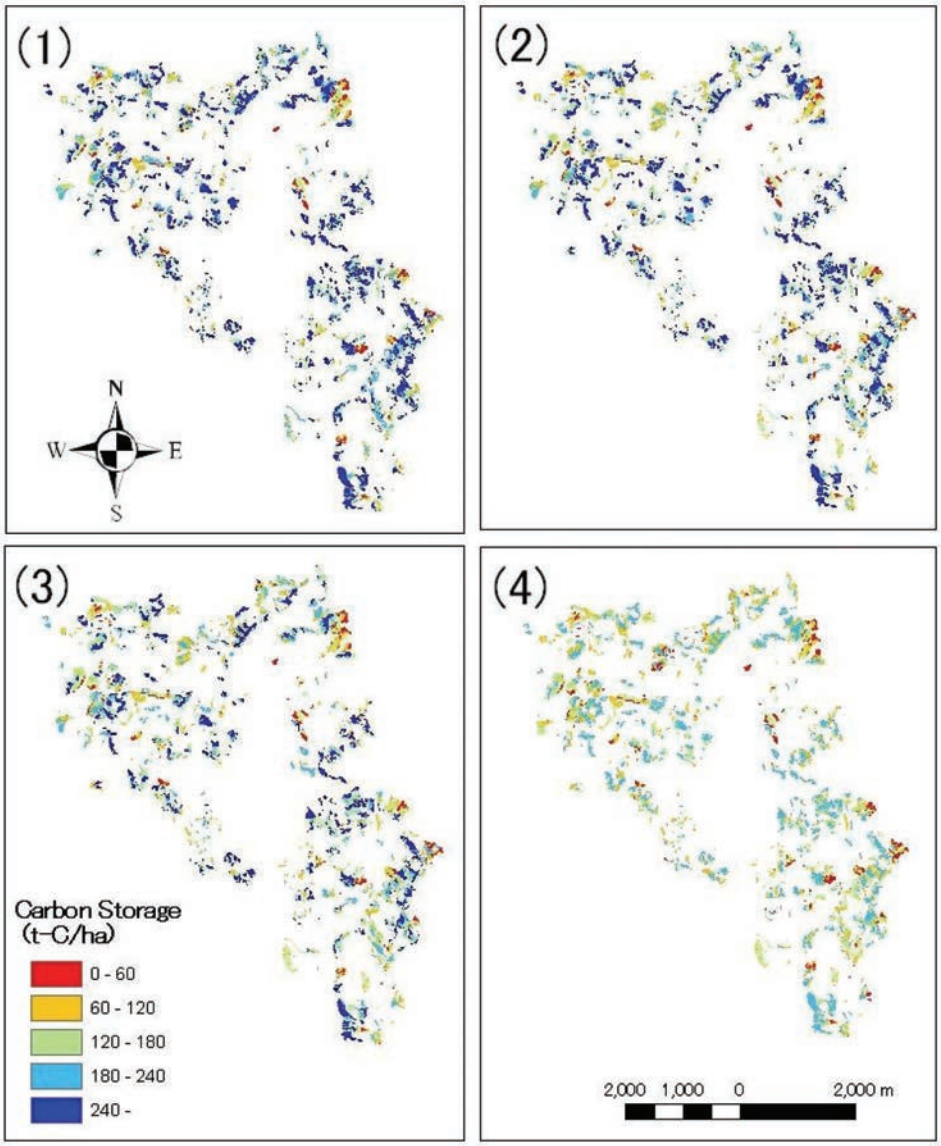

Fig. 3 Distribution of carbon storage under thinning regimes: (1) no. 1, (2) no. 2, (3) no. 3, and (4) no. 4

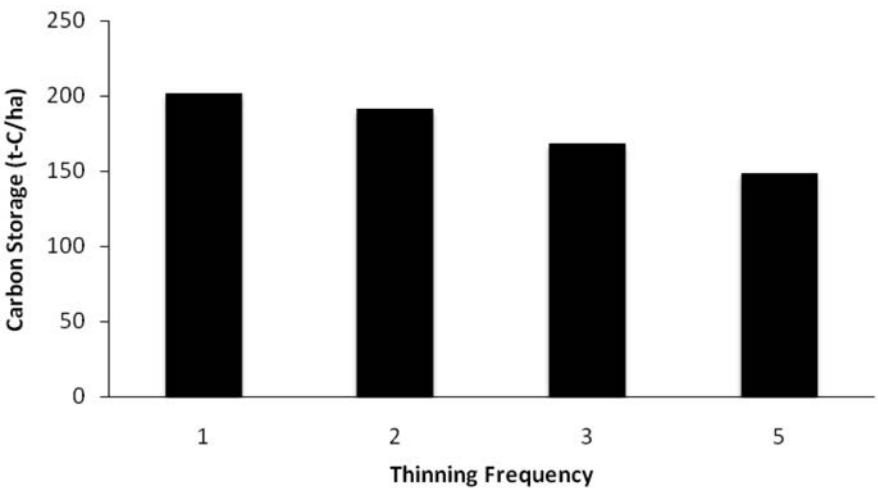

Fig. 4 Carbon storage under the four thinning regimes for all sugi plantations in Chiba Forest

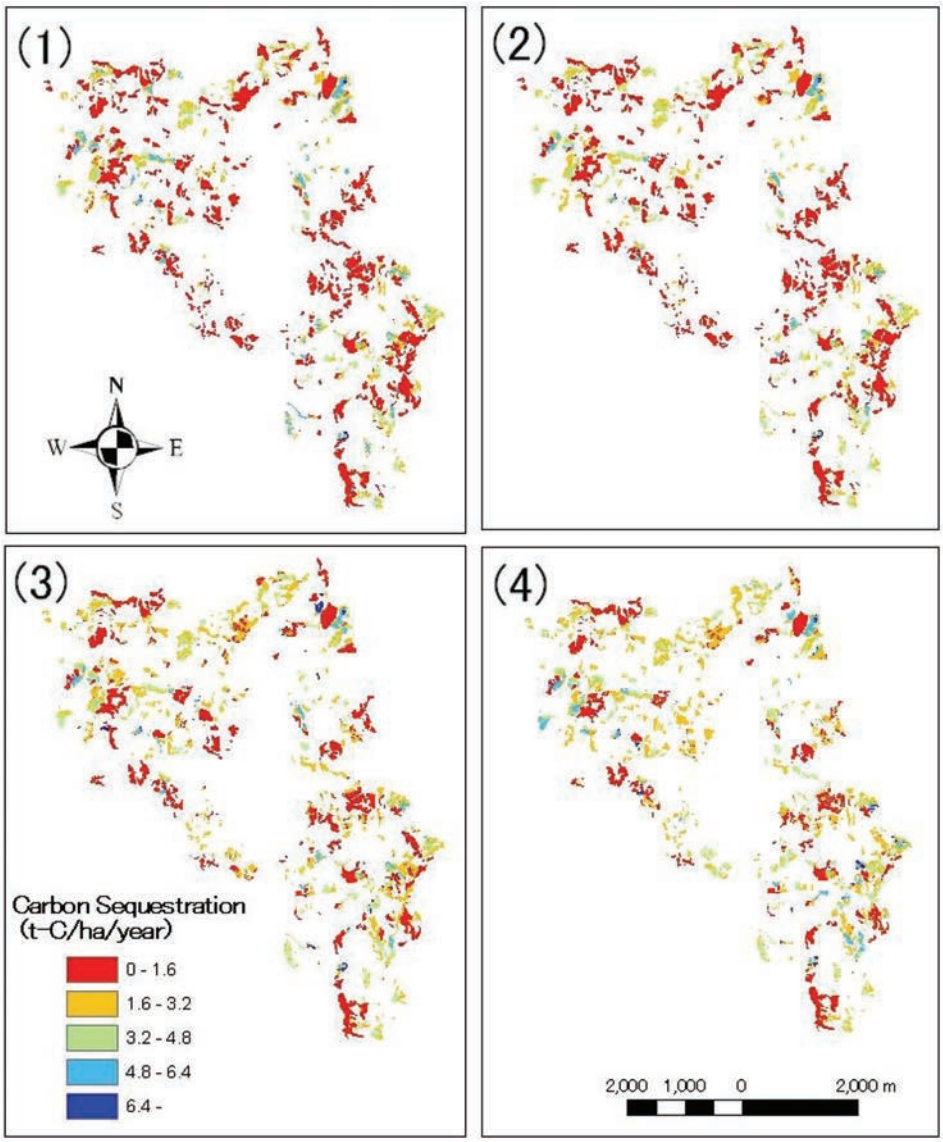

Fig. 5 Distribution of carbon sequestration under thinning regimes: (1) no. 1, (2) no. 2, (3) no. 3, and (4) no. 4

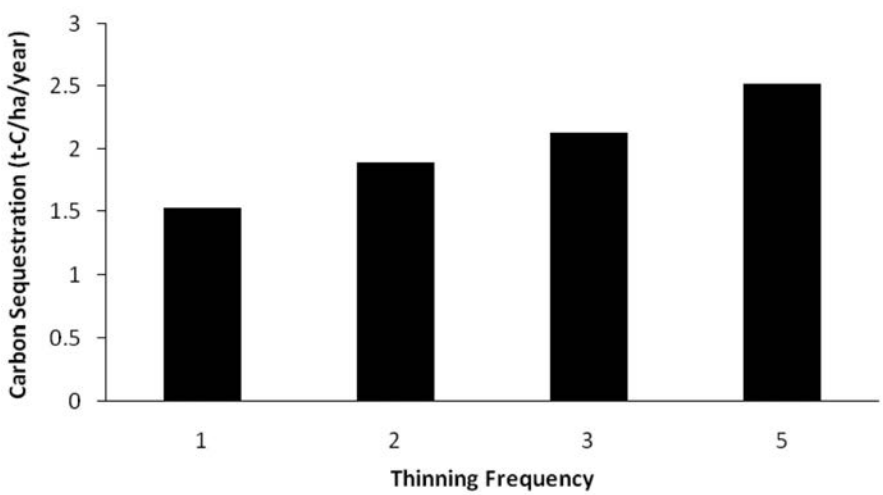

Fig. 6 Carbon sequestration under the four thinning regimes for all sugi plantations in Chiba Forest

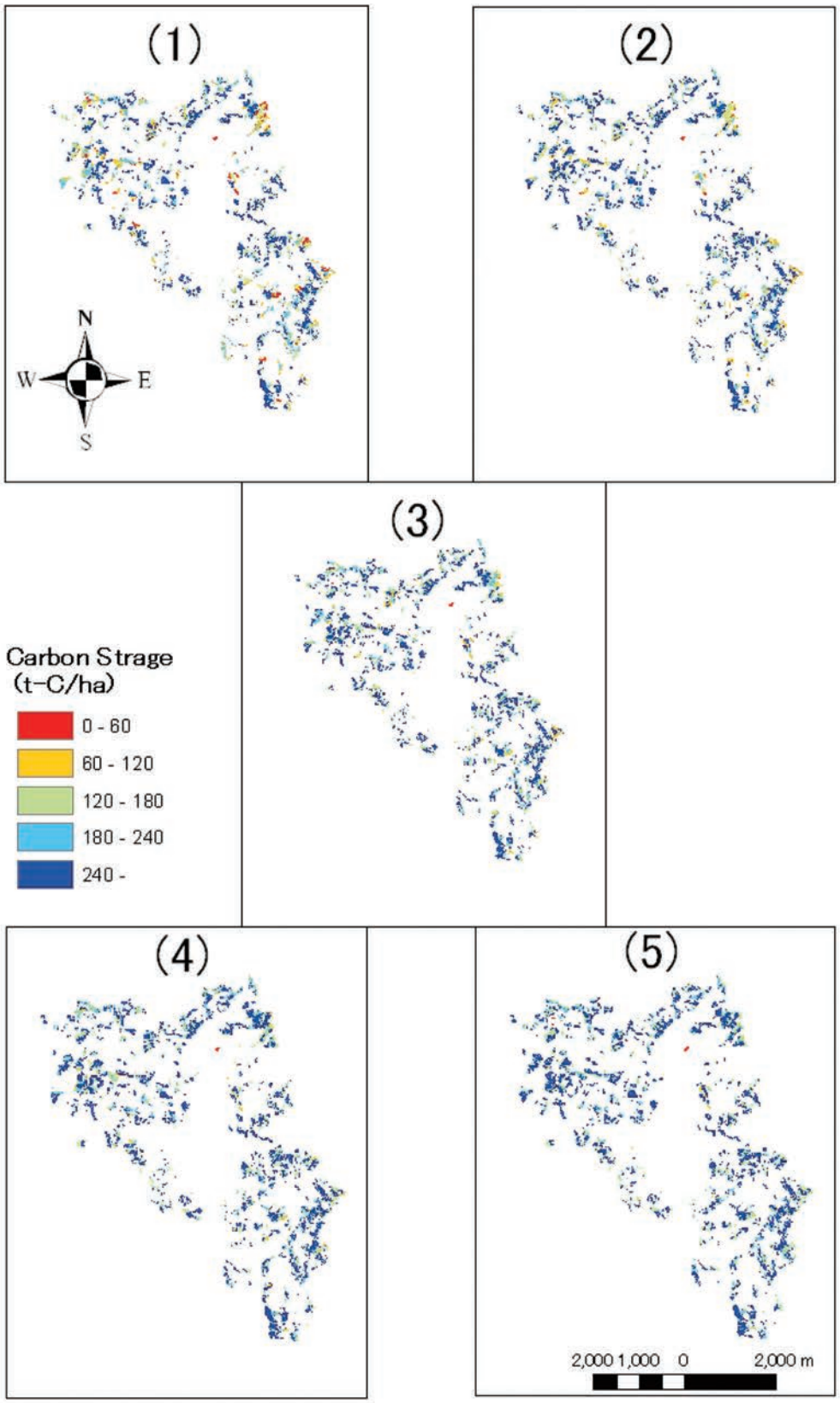

Fig. 7 Change in the distribution of carbon storage under thinning regime no. 1 over time (years): (1) at present, (2) after 10 years, (3) after 20 years, (4) after 30 years, and (5) after 40 years

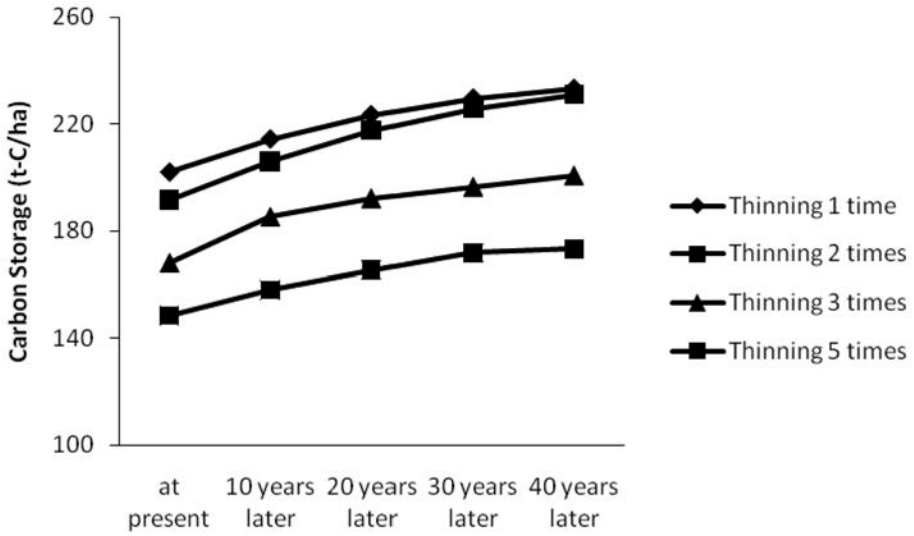

Fig. 8 Change in average carbon storage per unit area for all sugi plantations in Chiba Forest over time (years)

in carbon sequestration because trees require space to grow and the process of thinning creates the necessary space. Moreover, dead trees include those that died due to competition for light or sudden disturbances, such as damage from wind and snow (NISHIZONO *et al.*, 2008). Thus, thinning should be conducted frequently, at least in the short term, to cull suppressed trees and, in turn, increase levels of carbon sequestration. However, thinned trees ranged in age from young (20 years old) to old (70 to 90 years old), and DBH can increase just after thinning in trees even older than 60 years old (OSUMI *et al.*, 2000). Thus, thinning remains effective even in old plantation forests; it avoids declines in the growth of DBH caused by canopy closure and increases the number of large trees (KUNISAKI *et al.*, 1999).

This study demonstrated that frequent thinning can increase carbon sequestration but can also decrease carbon storage. Although thinning promotes the growth of remaining trees, strong thinning can decrease the growth of stand volume in plantation forests (KOSAKA *et al.*, 1967; AIBA *et al.*, 1988). Because the growth rate of trees can decline, particularly in old plantation forests, managers should avoid reducing stand growth through strong thinning (OSUMI *et al.*, 2000). Therefore, the strength of thinning should be chosen carefully so as to maximise the growth of remaining trees and minimise decreases in stand growth.

CONCLUSION

In this study, the site quality of plantation forests in terms of carbon sequestration was estimated using only site factors. Using the models presented here, site quality can be determined for treeless areas intended for future sugi plantations as well as for extant sugi plantations. Using GIS, the estimated carbon storage and sequestration for the study area were mapped, and a stand growth prediction system was designed based on estimated site quality and specified thinning regimes. The model can estimate not only present but also future carbon sequestration. DEM maps described changes in carbon storage and sequestration throughout the study area with various selected silvicultural systems or over time. The modelling and mapping approach presented here will prove useful for future evaluations of carbon sequestration in a variety of forest ecosystems.

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Article

Nationwide Yield Prediction by Adding Up Yields of Prefectures

Takuya Hiroshima*

ABSTRACT

The purpose of this study was to conduct a yield prediction from 2001 to 2050 on a national level by developing the Gentan probability-based model that combined yields of 47 prefectures. First, the Gentan probabilities were estimated for the 22 prefectures that had reliable harvesting data by the maximum likelihood method. Second, these prefectures were clustered into 3 groups based on the estimated Gentan probability patterns, and then the synthesized Gentan probabilities were estimated for each cluster from the aggregated stand areas and harvested areas of prefectures which belonged to the same cluster. Third, the other 25 prefectures without reliable harvesting data were classified into the preceding 3 clusters by discriminant analysis with socioeconomic explanatory variables. Fourth, harvesting volume were calculated for each prefecture based on the estimated Gentan probabilities: The former 22 prefectures employed the Gentan probabilities derived from their own harvesting data while the latter 25 prefectures employed the synthesized Gentan probabilities corresponding to their cluster number classified. Finally, a yield prediction was conducted from 2001 to 2050 based on the 5 scenarios that increased the means and standard deviations of Gentan probabilities in 47 prefectures by -10%, -5%, 0%, 5% and 10% every 5 years during the prediction periods. The results showed that harvesting areas decreased as the means and standard deviations got raised, and that the scenario of 0% increase brought about moderate result. To actualize this scenario, a standard rotation age in the Regional Management Plan should be raised 5-7% every 5 years for next 50 years.

Keywords: Gentan probability, harvesting data, national level, prefecture, yield

INTRODUCTION

The Gentan probability (Science and Technology Agency, 1961; 1963; Suzuki, 1959a; 1959b; 1972; 1973; 1979; 2002) has been applied for yield predictions in Japan. The Gentan probability is used in a yield prediction in the following way. The felling probability at the j-th age class, p_j, is the probability that a stand at the j-th age class is harvested, which is represented by

$$p_j = \frac{q_j}{r_j} \tag{1}$$

where q_j: the Gentan probability at the j-th age class, which is the probability that a planted stand survives the j-th age class and is harvested in the referred period; and r_j: the survival rate at the j-th age class, which is the probability that a planted stand survives beyond the j-th age class.

Given a stand area and a volume at the j-th age class, a_j and v_j, the total harvesting area and volume, c and v, are calculated by

$$c = \sum_j p_j a_j \tag{2}$$

and

$$v = \sum_j p_j a_j v_j . \tag{3}$$

The Gentan probability can be estimated by the maximum likelihood method using the following likelihood function, L, developed by Fujikake (2003) and Hiroshima (2006).

$$L = \prod_j p_j^{c_j} (1 - p_j)^{a_j - c_j} \tag{4}$$

where c_j is the harvesting area at the j-th age class in the referred period. Given the Gentan probability density function,

Corresponding author: Takuya Hiroshima
E-mail: hiroshim@uf.a.u-tokyo.ac.jp
* The University Forest in Chiba, Graduate School of Agricultural and Life Sciences, The University of Tokyo, 770 Amatsu, Kamogawa, Chiba 299-5503, Japan

$f(t)$, which represents a lifetime distribution such as the Gamma distribution, q_j tand r_j are calculated by

$$q_j = \int_{j-1}^{j} f(t)dt \tag{5}$$

and

$$r_j = 1 - \sum_{j=1}^{j-1} q_j = \int_{j-1}^{\infty} f(t)dt. \tag{6}$$

By substituting Eqs. (5) and (6) for Eq. (1), p_j can be expressed as the function of $f(t)$ in Eq. (4). Thus, if both stand area and harvested area by age classes during 1999-2003 are obtained from the harvesting data, the parameters of $f(t)$ are estimated and q_j tcan be calculated. For instance, the Gamma distribution including the parameters m and k:

$$f(t; m, k) = me^{-mt}\frac{(mt)^{k-1}}{\Gamma(k)} \tag{7}$$

is generally employed for $f(t)$.

To estimate the Gentan probabilities according to the above method, data on the stand area and harvested area by age classes during the referred period are needed. But not all of the prefectures can afford to obtain such harvesting data (Oka and Kuboyama, 2005). Because of this problem, when previous predictions on a national scale using the Gentan probability were done, data on stand area of private planted forests in Japan were treated as one group of forests (Society for the Study of Forest Planning, 1981; 1987; Society for the Study of Forest Basic Plan, 1997). However, doing the prediction in this way often caused a relatively large difference between prediction and observation of the actual conditions. If prediction on a national scale is conducted as an aggregation of each prefectural yield, prediction results would be improved.

Therefore, the purpose of this study was to conduct a yield prediction on a national level by combining all 47 prefectures using the Gentan probability. The prediction was conducted from 2001 to 2050 in private planted forests.

MATERIALS AND METHODS

Materials

We employed the harvesting data including the final cutting area by age classes yearly from 1999 to 2003 in the private planted forest for each prefecture (Oka and Kuboyama, 2005). Among these data, 22 prefectures were considered to have provided reliable harvesting data in which there are no records lacking and no major fluctuation among the total harvested areas during the 5 year period. The harvesting data also included information about area and volume by forest type: natural or planted, by cutting type: final cutting or thinning, by ownership: national or private, and by age classes: 1 – 21 class/5 years. Furthermore, we obtained statistics about the stand areas and growing stocks in 1999 for each prefecture from the Forestry Agency in Japan. We also obtained yield tables for each prefecture, which represent the average growing stocks in planted forests. In addition, the statistics about the amount of timber traded from 1999 to 2003 for each prefecture (Division of Statistics Maff Japan, 2005) were employed for later validation.

Estimation of the Gentan Probability

We employed the 22 prefectures with reliable data for the estimation of the Gentan probability density function parameters in line with the maximum likelihood method using Eqs. (4) – (7). The estimations were conducted for each prefecture; that is, 22 sets of Gentan probabilities were specified for each prefecture.

Clustering of estimated Gentan probabilities

A clustering with Ward's algorithm (Ward, 1963) was applied for grouping prefectures that had the similar Gentan probability pattern. The number of clusters was determined considering the Euclidean distances between clusters in the resultant hierarchical dendrogram.

The stand areas and harvested areas of prefectures which belonged to the same cluster were then aggregated, and synthesized Gentan probabilities were estimated again for each cluster by the following likelihood function:

$$L = \prod_j p_j^{\sum_j c_{i,j}} (1-p_j)^{\sum_j a_{i,j} - \sum_j c_{i,j}} \tag{8}$$

where i represented the unique IDs for the prefectures in the same cluster.

Classification of Other 25 Prefectures by a Discriminant Analysis

We classified the other 25 prefectures into the clustered groups by a discriminant analysis. In the analysis, the response variable was a category number of clustered groups corresponding to the 22 prefectures, which were treated as training data. The explanatory variables corresponding to every prefecture were average age class of planted forests (Shiraishi *et al.*, 2006) in 1999, volume of logs produced during 1999-2003 (Division of Statistics MAFF Japan, 2005), population in 2000 (Statistics Bureau MIC Japan, 2005), percentage of forest cover in 2000 (Division of Statistics MAFF Japan, 2001), forest workers employed in 2000 (Statistics Bureau MIC Japan, 2001) and planted forest areas in 1999 (Forestry Agency of Japan, 2001).

Validation

We calculated harvesting volumes during 1999-2003 for all 47 prefectures in Japan by Eq. (3). For the 22 prefectures with reliable harvesting data, the harvesting volumes were calcula-

ted based on the estimated Gentan probabilities in each prefecture. For the other 25 prefectures, harvesting volumes were calculated based on the synthesized Gentan probabilities associated with the clustered groups. The statistics about the amount of timber traded from 1999 to 2003 for each prefecture (Division of Statistics MAFF Japan, 2005) were converted to the volumes comparable with the above calculated ones. We conducted a validation by investigating the difference between those two log volumes.

Yield Prediction for 50 Years

We calculated harvesting areas from 2001 to 2050 for all 47 prefectures based on several scenarios. The 5 scenarios were provided that the means and standard deviations of the estimated Gentan probabilities in 47 prefectures increased by −10%, −5%, 0%, 5% and 10% every 5 years during the prediction periods. Note that negative percentages represented decrease of means and SDs. In addition, age class distributions of forest area and average harvested age classes were calculated in each scenario for further discussion.

RESULTS AND DISCUSSION

Estimated Gentan Probabilities

Fig. 1 shows the estimated Gentan probability distributions for 22 prefectures. The means ranged from approximately 17th in Aomori to 67th age class in Hyogo. Too small harvesting areas compared with large uncut areas leads to estimates of the

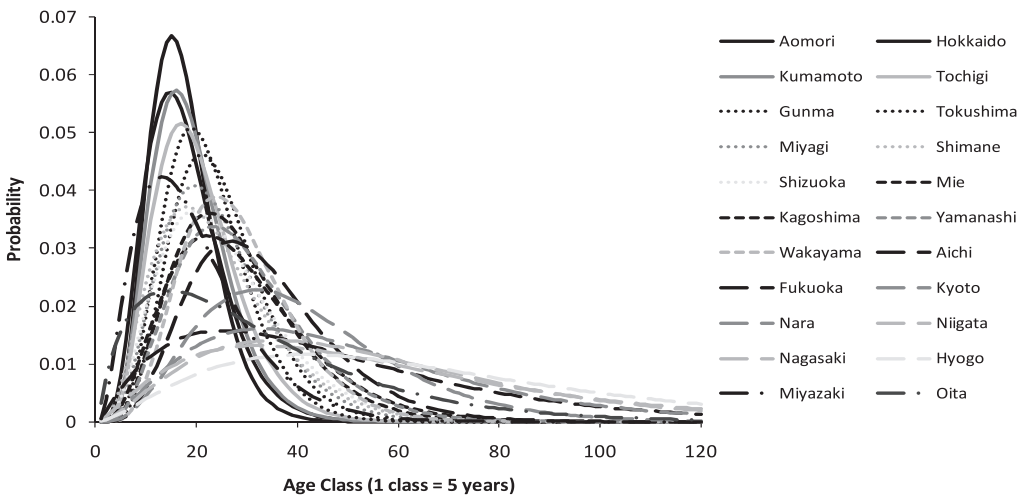

Fig. 1 Estimated Gentan probabilities for the 22 prefectures with reliable harvesting data

Fig.2 Synthesized Gentan probabilities estimated for three clusters
The original Gentan probabilities associated with 22 prefectures including Miyazaki and Oita are shown in pale gray lines.

Table 1 Parameters and coefficients of discriminant functions

Variable	Coefficient		Standardized Coefficient	
	Function 1	Function 2	Function 1	Function 2
Ave. Age Class	-0.08	0.23	-0.06	0.18
Log Volume	0.00	0.00	-4.20	2.66
Population	0.00	0.00	0.15	1.83
Forest Cover	-0.01	0.11	-0.05	1.10
Planted Forest Area	0.03	-0.03	3.67	-3.91
Constant	-1.15	-8.35		
P value	0.00	0.04		
Contribution	0.68	0.32		

Table 2 Result of discrimination

Prefecture	Group		Prefecture	Group	
	Training	Discrimination		Training	Discrimination
Hokkaido	1	1	Kyoto	3	3
Aomori	1	1	Osaka		3
Iwate		1	Hyogo	3	3
Miyagi	2	1	Nara	3	3
Akita		2	Wakayama	2	2
Yamagata		1	Tottori		2
Fukushima		1	Shimane	2	2
Ibaraki		1	Okayama		2
Tochigi	1	1	Hiroshima		3
Gunma	2	3	Yamaguchi		2
Saitama		3	Tokushima	2	2
Chiba		3	Kagawa		1
Tokyo		3	Ehime		2
Kanagawa		3	Kochi		2
Niigata	3	3	Fukuoka	3	3
Toyama		1	Saga		2
Ishikawa		2	Nagasaki	3	2
Fukui		2	Kumamoto	1	1
Yamanashi	2	2	Oita	#	1
Nagano		2	Miyazaki	#	1
Gifu		2	Kagoshima	2	2
Shizuoka	2	2	Okinawa		1
Aichi	3	3		Total Incorrect	3
Mie	2	2		Total Correct	17
Shiga		2		Correct Ratio	85%

lifetime distributions with high means according to the likelihood function of Eq. (4). The variances are roughly proportional to the corresponding means in the case of Gamma distribution.

Clustered Gentan Probabilities

The clustering was conducted except for Miyazaki and Oita because the shape of Gentan probabilities for the 2 prefectures were different from the other 20 prefectures. The resultant hierarchical dendrogram indicated that it took about 0.1 Euclidean distance until the initial 20 clusters agglomerated into 3 clusters, while it took about another 0.1 Euclidean distance until the 3 clusters agglomerated into 2. This means the similarity among the 3 clusters are low, so that the number of appropriate clusters was determined to be 3. The clusters were constituted as follows. Cluster 1: Hokkaido, Aomori, Tochigi and Kumamoto; cluster 2: Miyagi, Shizuoka, Shimane, Gunma, Tokushima, Yamanashi, Mie, Kagoshima and Wakayama; cluster 3: Niigata, Kyoto, Nagasaki, Nara, Hyogo, Aichi and Fukuoka. In this case, a smaller cluster number lead to larger harvesting area or more active forestry activities. Corresponding synthesized Gentan probabilities are illustrated in Fig. 2, where the original prefectures are shown in pale gray lines.

Classification of the Other 25 Prefectures

Table 1 shows the resultant parameters and coefficients of the discriminant functions where 2 linear functions were required to classify the prefectures into 3 groups. The variable of forest workers was eliminated from the explanatory variables. The standardized coefficients show that the variables of log volume and planted forest area are particularly influential in the discrimination.

Table 2 shows the result of discrimination: As three prefectures, Miyagi, Gunma and Nagasaki were misclassified among the 20 training prefectures, the correct ratio was 85% in total.

Validation

Fig. 3 shows the log volumes based on the calculations and estimates from the statistics during 1999-2003 for all 47 prefectures. The total calculated log volume was 24,277,000 m^3/5 years with the percentage error of 10.16% towards the estimates from statistics of 22,038,000 m^3. The total volume in the 22 prefectures with harvesting data had the percentage error of −3.05% and the other 25 had that of 33.21%. Among the latter 25 prefectures, Iwate, Yamagata, Ibaraki and Toyama had large differences of 510,000 548,000 478,000 and 332,000 m^3 respectively between the calculations and statistics. If these four prefectures are removed, the error of the other 21 decreased to 12.90% in total.

As Iwate, Yamagata, Ibaraki and Toyama belong to cluster 1, which produced the largest yields among the three clusters, their errors became particularly large. For reference, if the Gentan probabilities of these four prefectures are replaced by those of cluster 2, the differences between calculations and statistics for the four prefectures are decreased to −443,000 −99,000 −23,000 and 94,000 m^3 respectively. This implies that the discriminated cluster of 1 except Iwate may be misclassified considering that the discrimination functions had the correct ratio of 85% at most. According to this result, Yamagata,

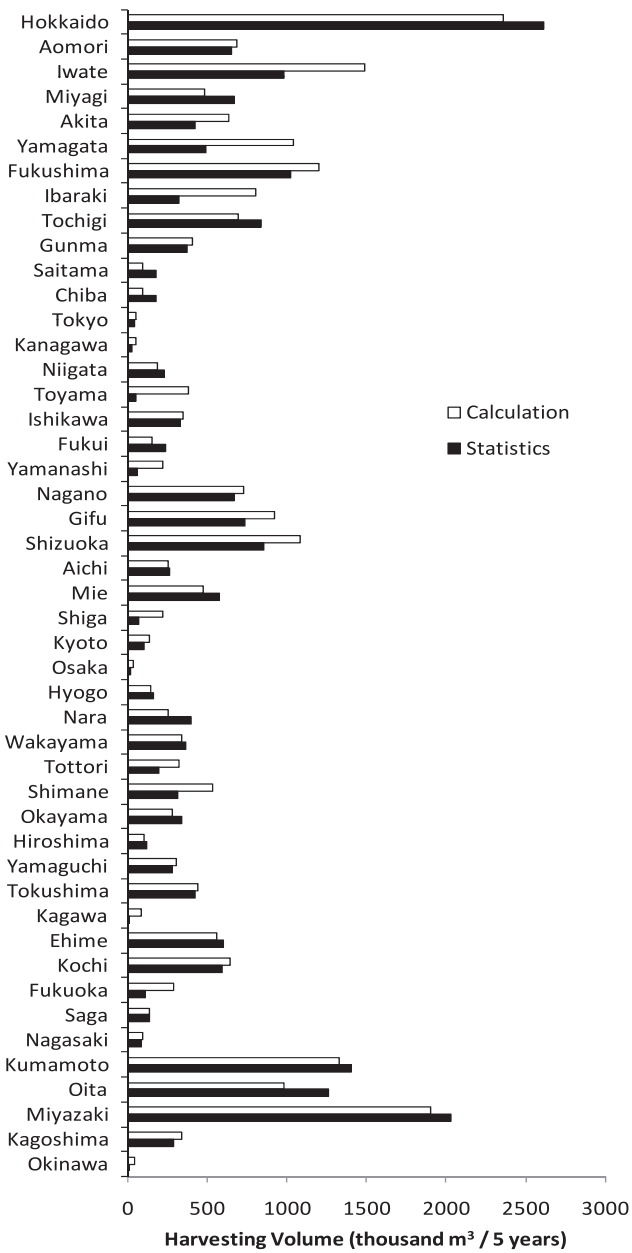

Fig. 3 Log volumes based on the calculations and estimates from the statistics during 1999-2003 for all 47 prefectures

Ibaraki and Toyama were assigned the synthesized Gentan probability of cluster 2 in the yield prediction.

Generally, the total error of 10.16% is acceptable in the yield prediction on a national level.

Yield Prediction and Recommendation

Fig. 4 shows changes in the predicted harvesting area for 50 years based on the 5 scenarios. For simplicity, each graph represents total of 47 prefectures. Harvesting areas decreased as the means and standard deviations of the Gentan probabilities got raised, with the results that harvesting areas in 2046 had about 10 times, 6 times, 3 times, almost even and 0.4 times larger than those in 2001 for the scenarios of −10%, −5%, 0%, 5% and 10% increase, respectively.

Fig. 5 shows the age class distributions of forest areas in 2046 and 2001 for the 5 scenarios in the total of 47 prefectures. The peaks in the 17th age class became large as the means and SDs of the Gentan probabilities got raised, and the younger forests became small to the contrary.

Fig. 6 shows changes in the average harvested age classes for the 5 scenarios in the total of 47 prefectures, which is calculated by the sum products of harvested age class i^* harvested area at age class i / total harvested area. Average harvested age classes increased as the means and SDs of the Gentan probabilities got raised, but all of them were basically on the upward trends except the latter part of −10% scenario. In addition, we confirmed that the SDs of harvested age classes were less than 3.0 at most years in all scenarios.

To sum up, the scenario of 0% increase that keeps the current Gentan probability distribution brought about moderate results considering predicted harvested areas and age class distributions of forest area. It is important that an average harvested age is politically controllable as a standard rotation age in the Regional Management Plan. Forest owners should make harvest schedules in their forest management plans in accordance with a standard rotation age in the Regional Management Plan. To actualize the scenario of 0% increase, it is required to raise standard rotation ages politically by 5–7% for every 5 years in line with Fig. 6.

CONCLUSION

In this study, we conducted a yield prediction on a national level by combining the yields of each prefecture using the Gentan probability. The procedure for the prediction is summarized as follows. First, the Gentan probabilities were estimated for the 22 prefectures with reliable harvesting data. Second, these prefectures were clustered into 3 groups by a clustering method based on the estimated Gentan probability patterns, and then the synthesized Gentan probabilities were estimated for each cluster. Third, the other 25 prefectures without reliable harvesting data were classified into the preceding 3 clusters by discriminant analysis with socioeconomic

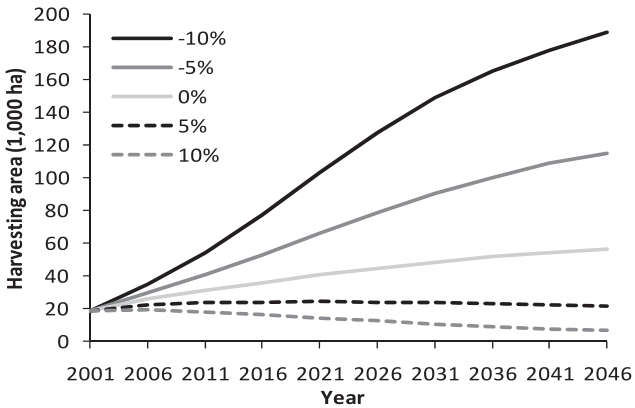

Fig. 4 Changes in the predicted harvesting area in the total of 47 prefectures for 50 years based on the 5 scenarios
The legends represent the increase of means and standard deviations of the Gentan probabilities by X% every 5 years.

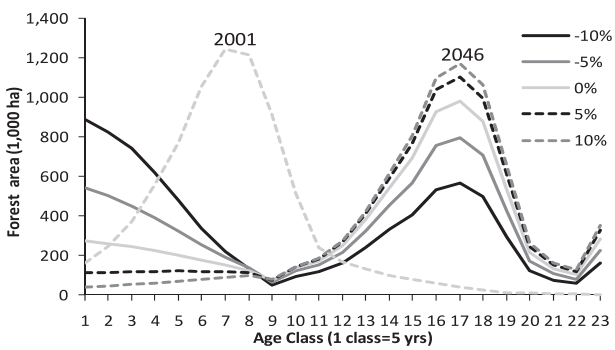

Fig. 5 Age class distributions of forest areas in the total of 47 prefectures in 2046 and 2001 for the 5 scenarios

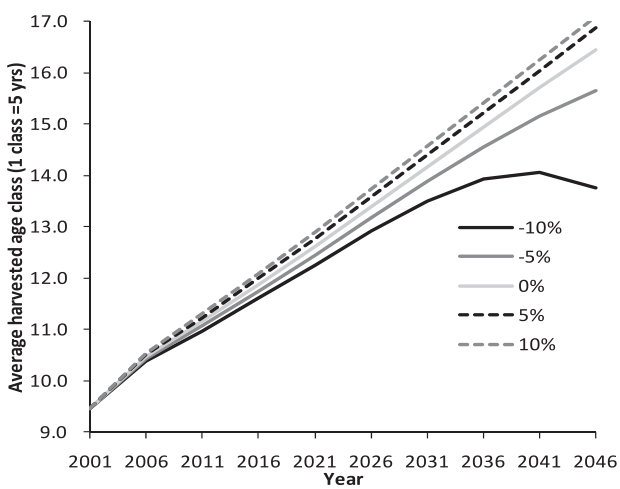

Fig. 6 Changes in the average harvested age classes for the 5 scenarios in the total of 47 prefectures

explanatory variables. Forth, harvesting volume were calculated for each prefecture based on the estimated Gentan probabilities: The former 22 prefectures employed the Gentan probabilities derived from their own harvesting data while the latter 25 prefectures employed the synthesized Gentan probabilities derived from the harvesting data of the clustered former prefectures. Finally, a yield prediction was conducted for 50 years based on several scenarios that increased the means and standard deviations of the Gentan probabilities in 47 prefectures. The prediction results showed that harvesting areas decreased as the means and standard deviations got raised, and that the scenario of 0% increase brought about moderate result.

ACKNOWLEDGEMENTS

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Article

Stand Structure and Geographic Conditions of Natural Selection Forests in Central Hokkaido, Northern Japan

Toshiaki Owari*, Masaki Matsui*, Hiroshi Inukai* and Mikio Kaji*

ABSTRACT

Selection forest is a forest managed with the uneven-aged silvicultural system, in which trees are removed individually from a large area periodically. Selection system has been used to manage natural forests in Hokkaido, northern Japan. This study demonstrated the characteristics of natural selection forests in central Hokkaido. A case analysis was conducted at the University of Tokyo (UT) Hokkaido Forest to closely examine the structure and geography of selection stands. We used a total of 1,382 sample plots that had established in selection stands during 1996–2005 and the spatial information on stand classification with 10-m grid digital elevation model. We calculated the mean dominance and density of trees with DBH ≥ 5 cm, which were 30.7 m^2 ha^{-1} and 792 individuals ha^{-1}, respectively. Juveniles (Height ≥ 1.3 m and DBH < 5 cm) had a mean density of 561 individuals ha^{-1}. An asymmetric and peaked distribution was observed in tree and juvenile density. The predominant tree species included Sakhalin fir (*Abies sachalinensis*), Yezo spruce (*Picea jezoensis*), Japanese linden (*Tilia japonica*), and painted maple (*Acer mono*). An inverse J-shaped diameter distribution was maintained in tree density. Selection stands were mostly located on an area between 300–600 m a.s.l..

Keywords: geographic condition, selection forest, stand structure, Hokkaido

INTRODUCTION

Selection forest is a forest treated and managed under the uneven-aged silvicultural system called 'selection system', in which trees are selected to be removed individually or in small groups from a large area periodically (ZINGG, 1999; ZINGG *et al.*, 1999). In a selection forest, trees with all diameter (or age) classes are closely intermixed over a small area (SCHÜTZ, 2006). The whole area is continuously covered, the growing stock changes only on small areas, and consecutive regeneration and harvesting are possible (ZINGG *et al.*, 1999). A relatively steady state of structure and functions can be realized over time as compared with even-aged forest management (O'HARA *et al.*, 2007).

Selection forests are present in central Europe including Austria, France, Germany, Slovenia, and Switzerland, where the main species are European silver fir (*Abies alba* MILL.), Norway spruce (*Picea abies* (L.) H. KARST.), and European beech (*Fagus sylvatica* L.) (SCHÜTZ, 2001). The management of northern hardwood forests uses selection system in North America (NYLAND, 1998), where sugar maple (*Acer saccharum* MARSH.) and American beech (*Fagus grandifolia* EHRH.) are key tree species. Selection forests can be found in various parts of Japan (OHGANE, 1981). In Hokkaido, northernmost Japan, natural forest covers an area of 3.7 million ha. It is mainly comprised of multi-aged and mixed stands, and selection system has been widely employed since the early 20th century as a major option to manage natural forests (YOSHIDA *et al.*, 2006). Although previous studies portrayed selection forests in Hokkaido (e.g., ISHIBASHI, 1999; YAMAMOTO *et al.*, 1995; YOSHIDA *et al.*, 2006), there are limited data on their structural and geographic features at the forest management scale.

The purpose of this study was to demonstrate the basic characteristics of selection forests in central Hokkaido. A case analysis was conducted at the University of Tokyo (UT) Hokkaido Forest to closely examine the structure (tree dominance and density, species composition, diameter distribution) and geography (elevation, inclination, slope aspect) of selection stands. Because of their greater complexity and heterogeneity

Corresponding author: Toshiaki Owari
E-mail: owari@uf.a.u-tokyo.ac.jp
* Hokkaido Forest, Graduate School of Agricultural and Life Sciences, The University of Tokyo, 2 jo Kita 1, Yamabe, Furano, Hokkaido 079-1561, Japan

than even-aged stands (O'HARA *et al.*, 2007), we aimed to represent spatial variations in selection forests. Stand-level inventory data that had collected throughout the UT Hokkaido Forest was used for the analysis. We concluded by briefly characterizing selection forests in central Hokkaido in comparison with central Europe.

MATERIALS AND METHODS

The UT Hokkaido Forest is located in Furano, central Hokkaido (43°10–20′N, 142°18–40′E, 190–1,460 m a.s.l.), with an area of 22,733 ha. According to observations at the Arboretum (43°13′N, 142°23′E, 230 m a.s.l.), mean annual temperature and precipitation during 1996–2005 were 6.3 ℃ and 1,254 mm, respectively (THE TOKYO UNIVERSITY FOREST IN HOKKAIDO, 2007). Snow (approximately 1 m in depth) covers the ground from November to April. The typical substrate and soil type are welded tuff (GEOLOGICAL SURVEY OF JAPAN, 2003) and dark and brown forest soil (ASAHI, 1963). It is situated in an area of mixed forest with coniferous and broad-leaved species between the cool-temperate and the sub-boreal zone, and is mostly covered by natural forests. The forest floor is often occupied by dwarf bamboo *Sasa senanensis* (FRANCH. & SAVAT.) REHD. or *Sasa kurilensis* (RUPR.) MAKINO & SHIBATA.

Long-term and large-scale experiments of the stand-based forest management system (SFMS) have been conducted at the UT Hokkaido Forest since 1958. The idea behind the SFMS is that management should be adaptive to the conditions of each stand for maximizing multiple public and economic functions of forest ecosystems (TAKAHASHI, 2001). A natural forest can be classified into several stand types according to the difficulty of natural regeneration, site conditions, and timber quality. A stand in which natural regeneration is expectable so that selection cutting is applicable can be classified as selection stand.

This study investigated all selection stands that had been classified and managed during the 11th management planning period (1996–2005). Stand classification was conducted based on careful on-site observations with intensive ground surveying. The cutting cycle was either 10 or 20 years, depending upon site conditions and the growth rate of stands. The rate of removals was normally 16–17% of the growing stock, which was less than the growth rate (THE TOKYO UNIVERSITY FOREST IN HOKKAIDO, 1997).

We used a total of 1,382 sample plots that had established in selection stands one year before harvesting (1995–2004) (Fig. 1). The plot size was typically 0.25 ha (50 m × 50 m), and the species and diameter at breast height (DBH) for all living trees with DBH ≥ 5 cm were recorded in each plot. The number of juveniles (≥ 1.3 m in height and < 5 cm in DBH) by tree species were also recorded. Single-tree selection cutting had been conducted on the selection stands at least 1–3 times before the measurements.

Tree dominance (represented by the sum of basal areas), tree density, and juvenile density were examined by calculat-

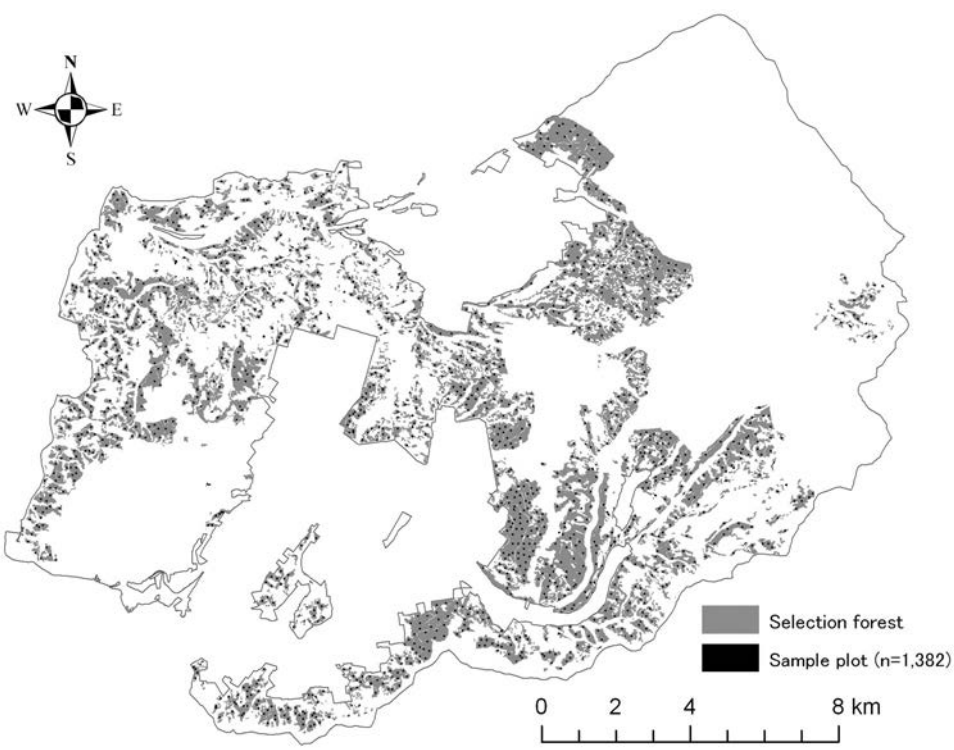

Fig. 1 Location of selection forests and sample plots

ing the frequency distribution of sample plots. The basic statistics (mean, standard deviation, minimum, maximum, and median) with skewness and kurtosis were also computed. Skewness characterizes the degree of asymmetry of a distribution around its mean, and kurtosis measures the relative peakiness or flatness of a distribution compared with the normal distribution (BROWN, 1997). The skewness-kurtosis test examined the normality hypothesis. Species composition was analyzed by listing observed tree species with their dominance, density and constancy (percentage occurrence in sample plots). Diameter distribution was investigated by calculating tree dominance, density and consistency according to the DBH classes (2 cm intervals).

The analysis of geographic conditions used the spatial information on selection forests, which was developed by converting the management planning (stand classification) maps into polygon features of the geographic information system (GIS) (OWARI *et al.*, 2009). Elevation, inclination, and slope aspect were examined through spatial analyses using GIS software ArcGIS 9.3 (ESRI Corp., CA, USA) with 10-m grid digital elevation models of GISMAP Terrain Ver. 2.00 (Hokkaido Chizu Co. Ltd., Asahikawa, Japan).

RESULTS

Tree Dominance and Density

The frequency distribution of 1,382 sample plots by tree dominance was shown in Fig. 2. We observed a mono-modal distribution, having a mean basal area of 30.7 m^2 ha^{-1}. Skewness was close to zero so that the distribution was quite symmetric. Positive kurtosis indicated a relatively peaked distribution. The skewness-kurtosis test rejected the normality hypothesis ($p < 0.001$). Plots with a basal area of > 50 or < 20 m^2 ha^{-1} were rare. The mean growing stock was 281.4 m^3 ha^{-1}.

The mean density of trees with DBH ≥ 5 cm was 792 individuals ha^{-1} (Fig. 3). Even though a mono-modal frequency distribution was depicted, positive skewness and kurtosis indicated a relatively asymmetric and peaked distribution. The normality hypothesis was rejected ($p < 0.001$).

The plot frequency according to the juvenile density had a

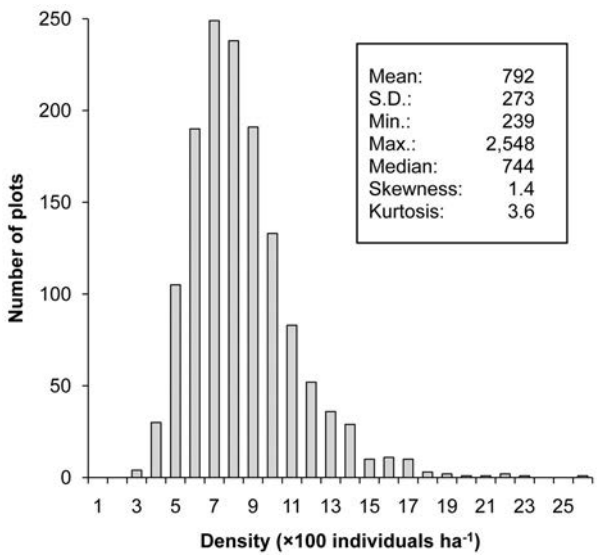

Fig. 3 Frequency of observed sample plots according to the tree density
Living individuals with DBH ≥ 5 cm were investigated.

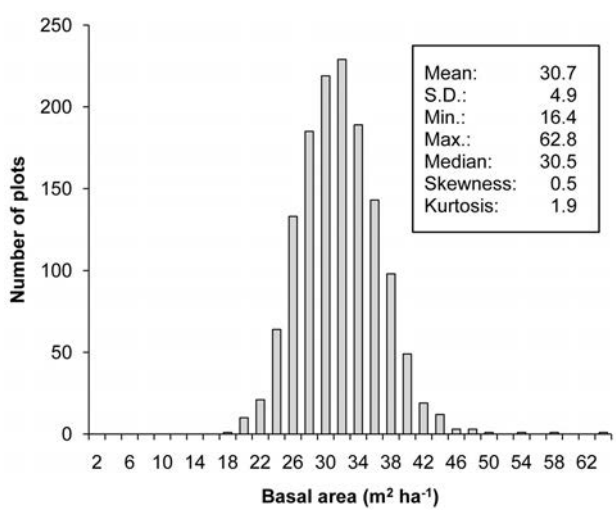

Fig. 2 Frequency of observed sample plots according to the tree dominance
Living individuals with DBH ≥ 5 cm were investigated.

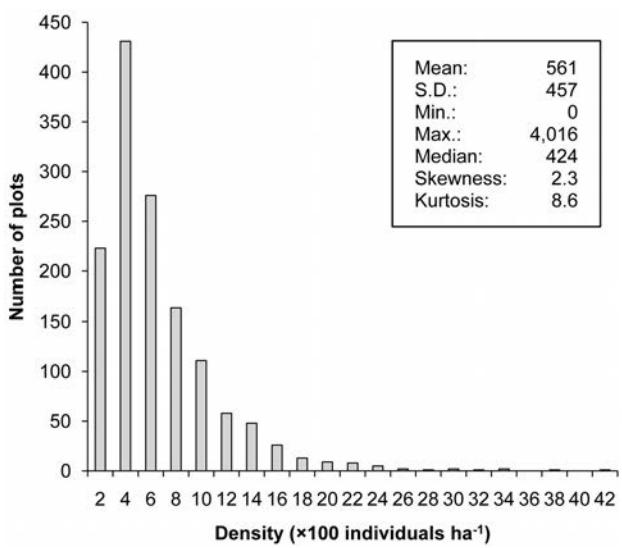

Fig. 4 Frequency of observed sample plots according to the juvenile density
Living individuals with DBH < 5 cm and Height ≥ 1.3 m were investigated.

mono-modal and skewed distribution (Fig. 4). Highly positive skewness and kurtosis indicated that the majority of the densities were concentrated on the low value end. The mean juvenile density of 561 individuals ha^{-1} was relatively large compared to its median value (424 individuals ha^{-1}). The null hypothesis of normality was rejected ($p < 0.001$).

Species Composition

Conifers and broad-leaved trees had a mean basal area of 17.5 and 13.2 m^2 ha^{-1}, and a mean density of 373 and 419 individuals ha^{-1}, respectively. Despite their superior dominance, a relatively small number of conifers were observed in selection stands. Broad-leaved trees took a relatively large share in juveniles, having 375 individuals ha^{-1}. Conifers had 186 juveniles ha^{-1} on average.

A total of 45 tree species were recorded, and we listed common tree species observed in sample plots as Table 1. *Abies sachalinensis* (Fr. Schm.) Masters had the highest tree dominance, followed by *Picea jezoensis* (Sieb. & Zucc.) Carr. These two conifers gained 55% of the tree dominance in selection stands. The tree and juvenile densities of *P. jezoensis* were relatively low despite its high dominance. *A. sachalinensis* trees and juveniles occurred at nearly all sample plots, while we did not observe *P. jezoensis* juveniles at 30% of the plots. Other coniferous species included *Picea glehnii* Masters and *Taxus cuspidata* Siebold & Zucc..

Among broad-leaved tree species, *Tilia japonica* (Miq.) Simonkai (recorded as *Tilia* spp.) and *Acer mono* Maxim. achieved relatively high dominances and densities. These tree species were observed in most of the sample plots. Other broad-leaved tree species with relatively high dominance included *Kalopanax pictus* (Thunb.) Nakai, *Quercus crispula* Blume, and *Ulmus laciniata* (Trautv.) Mayr (recorded as *Ulmus* spp.). In these species, juveniles had a relatively low density and occurred only at 34–41% of the plots.

Table 1 Tree species observed in selection stands

Species	Trees			Juveniles	
	Mean dominance m^2 ha^{-1}	Mean density individuals ha^{-1}	Constancy %	Mean density individuals ha^{-1}	Constancy %
Abies sachalinensis	12.8	298	100	162	99
Picea jezoensis	4.1	56	85	17	70
Tilia spp.	3.2	95	97	77	95
Acer mono	2.3	62	98	54	90
Kalopanax pictus	1.0	16	86	7	41
Quercus crispula	0.9	11	66	5	34
Ulmus spp.	0.9	21	77	8	38
Other Acer spp.	0.5	31	87	58	72
Magnolia obovata	0.5	22	80	17	72
Betula maximowicziana	0.5	8	57	2	17
Ostrya japonica	0.5	8	38	3	16
Picea glehnii	0.4	6	31	2	15
Prunus ssiori	0.4	20	57	31	63
Sorbus commixta var. *rufoferruginea*	0.3	27	78	22	67
Other *Prunus* spp.	0.3	14	68	7	42
Aria alnifolia	0.2	12	67	8	43
Betula ermanii	0.2	5	21	4	13
Fraxinus mandshurica var. *japonica*	0.2	4	27	2	12
Cercidiphyllum japonicum	0.2	3	28	1	15
Acanthopanax sciadophylloides	0.2	11	58	7	37
Magnolia kobus var. *borealis*	0.2	9	57	17	55
Phellodendron amurense	0.2	8	62	2	24
Taxus cuspidata	0.1	10	56	4	29

Common tree species (BA $\geq$ 0.1 m^2 ha^{-1}) were listed. Constancy is the percentage occurrence in 1,382 sample plots.
Tilia spp.: *T. japonica* and *T. maximowicziana*; *Ulmus* spp.: *U. laciniata* and *U. davidiana* var. *japonica*; Other *Acer* spp.: *A. japonicum* and *A. palmatum* var. *amoenum*; Other *Prunus* spp.: *P. sargentii* and *P. maximowiczii*.

Diameter Distribution

The mean dominances of conifers and broad-leaved trees by DBH class (2 cm intervals) were shown in Fig. 5. A monomodal distribution was observed in each species group, having a mode at 40 and 30 cm of DBH, respectively. The dominance of conifers exceeded that of broad-leaved trees at DBH classes between 24–68 cm, and vice versa at DBH ≤ 22 cm and ≥ 70 cm.

As to the mean tree densities by DBH class, we observed an inverse J-shaped distribution curve in both conifers and broad-leaved trees (Fig. 6). A relatively large number of broad-leaved trees were observed at DBH classes of less than 22 cm. An inverse S-shaped curve was drawn for the constancy distribution (Fig. 7). Constancy decreased gradually as the DBH becomes large. Broad-leaved trees had a relatively large constancy in small DBH classes, while conifers occurred more in sample plots at DBH classes between 26–66 cm.

Geographic Conditions

Selection stands had an area of 5,111 ha, accounting for 23% of the UT Hokkaido Forest. The spatial distribution by elevation class was shown in Fig. 8. The mean elevation was 465 m a.s.l. with a range between 192–842 m a.s.l.. Of the selection forests, 91% were located on 300–600 m a.s.l..

The mean inclination of selection stands was 14.9 degree. 90% of the selection stands attributed less than 30 degree, in which the distribution was fairly even (Fig. 9). The slope aspect was somewhat biased to the west according to the general trend at the UT Hokkaido Forest (Fig. 10). 52% of selection stands were located on a northwest-west-southwest facing slope.

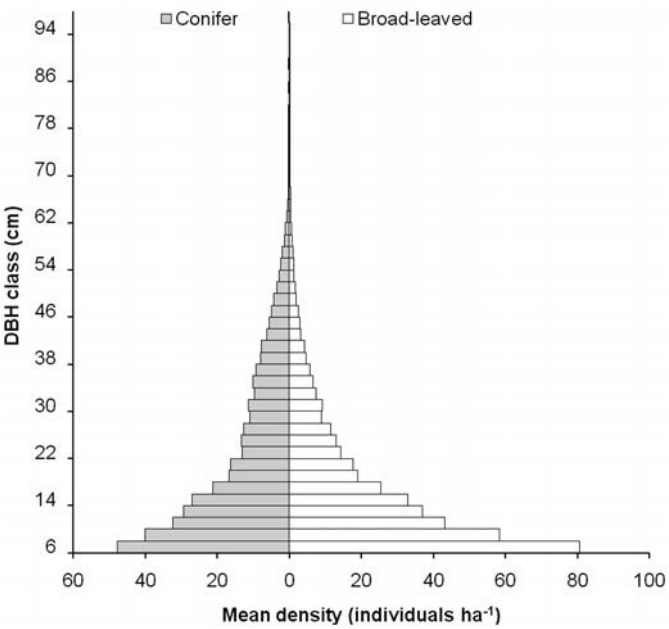

Fig. 6 Mean densities of coniferous and broad-leaved trees by diameter class

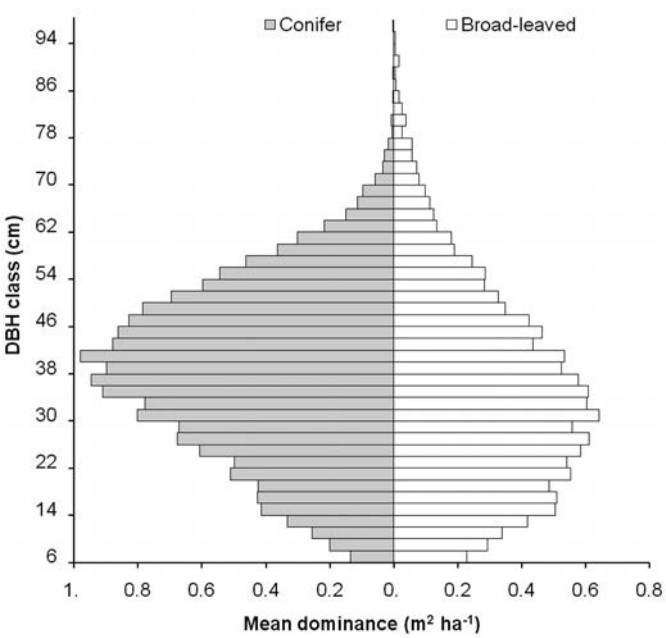

Fig. 5 Mean dominances of coniferous and broad-leaved trees by diameter class

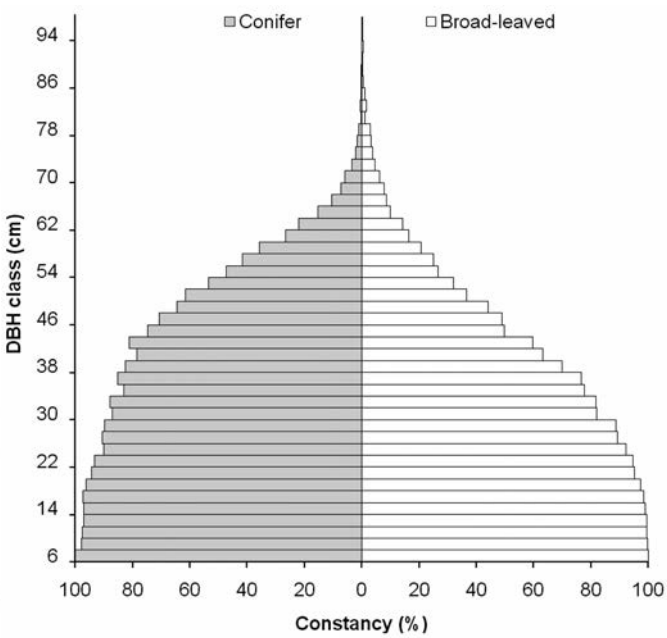

Fig. 7 Constancies of coniferous and broad-leaved trees by diameter class

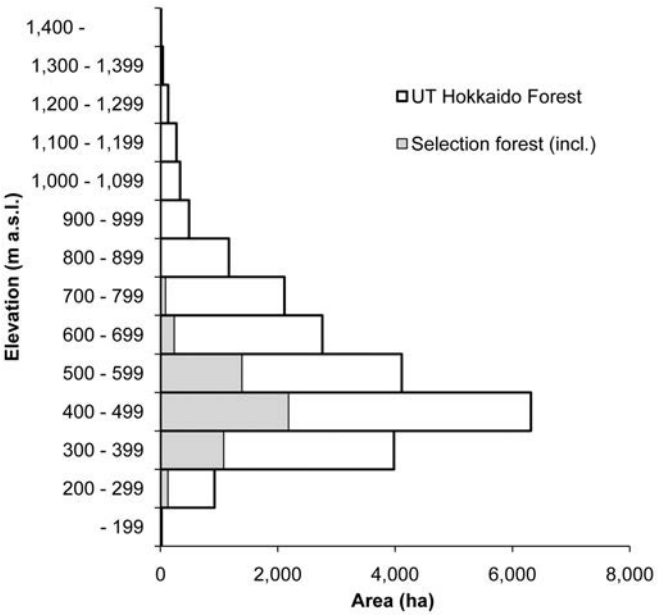

Fig. 8 Area of selection forests by elevation

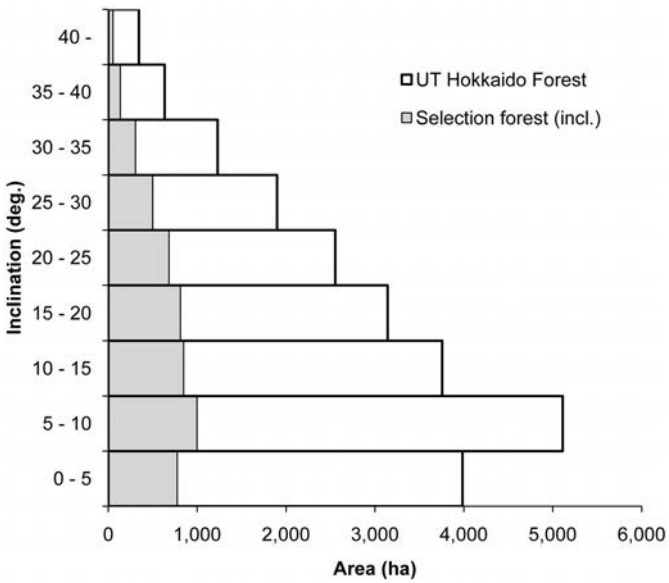

Fig. 9 Area of selection forests by inclination

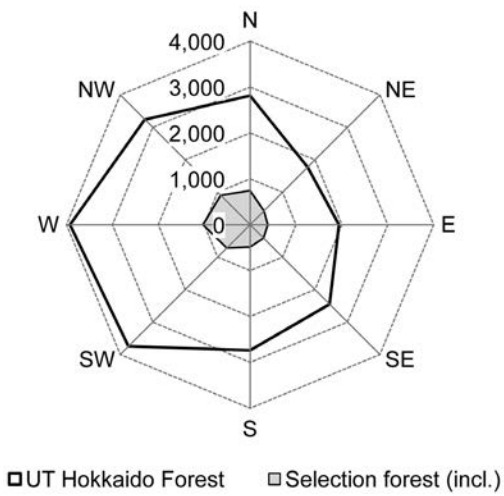

Fig. 10 Area of selection forests by slope aspect

DISCUSSION

Results in this study are consistent with previous research reporting tree dominance and density of selection forests in Hokkaido (ISHIBASHI, 1999; YOSHIDA *et al.*, 2006). We observed a relatively low dominance with high density compared to selection (or plenter) forests in Switzerland (O'HARA *et al.*, 2007), where conifers with large diameter are rather dominant. Although the initial idea of selection system in Hokkaido was heavily influenced by European experiences (OHGANE, 1981), the structural differences of selection forests between two regions are evident. YAMAMOTO *et al.* (1996) analyzed the structure of selection stands at the UT Hokkaido Forest during 1986–1995, using 1,179 sample plots established under the 10th forest management plan. The mean tree dominance and density were 28.0 m^2 ha^{-1} and 754 individuals ha^{-1}, respectively, both of which were relatively low compared to our results. The increase in dominance and density after a decade may be due to the positive effects of selection cutting and canopy opening that could promote growth and regeneration. A weak harvesting intensity can be in favor of tree dominance and density.

The normality hypothesis was rejected for the tree dominance and density of selection forests. Positive kurtosis can be affected by the single-tree selection policy, according to which trees were removed intensively from a dense stand with high dominance and were not removed in a sparse stand with low dominance. This policy may have resulted in the concentration on moderate dominance and density. Positive skewness may be due to recurrent selection cutting, which can cause the reduction of small trees in a stand. In fact, the mean juvenile density during 1986–1995 was large (717 individuals ha^{-1}) (YAMAMOTO *et al.*, 1996) relative to our results. This may be because selection forests partly suffered from unsuccessful regeneration caused by thick floor vegetation (i.e., *Sasa* spp.) (HOSAKA *et al.*, 2008) and injuries to residual trees by logging operations (FUKUSHI *et al.*, 1997).

Two conifers of Sakhalin fir (*A. sachalinensis*) and Yezo spruce (*P. jezoensis*) with shade-tolerant broad-leaved tree species such as Japanese linden (*T. japonica*), painted maple (*A. mono*) and Manchurian elm (*U. laciniata*) were growing in selection forests in central Hokkaido. Beech, a common tree species in central Europe, was not growing naturally in the UT Hokkaido Forest. Shade-intolerant broad-leaved tree species of Japanese oak (*Q. crispula*) and castor aralia (*K. pictus*) also had

relatively high dominance. A large-scale natural disturbance (i.e., typhoon or fire) happened in the past probably gave an opportunity to introduce. Since these tree species had few juveniles in selection stands, their dominances may be decreasing in the future.

An inverse J-shaped diameter distribution that can be a desirable size structure as selection forests (O'Hara and Gersonde, 2004) was maintained in tree density. Although the mean juvenile density seems to be decreasing, the number of succeeding trees may still be secured for the recovery of size structure after selection cutting. We observed a relatively large number of broad-leaved trees in small diameter classes. Small-scale canopy disturbances by selection cutting may affect positively the regeneration of broad-leaved tree species. The number of conifers exceeded in middle and large diameter classes. The growth rate of conifers is high enough to fill trees removed by selection cutting (Ishibashi, 1990).

Our results concerning geographic conditions were consistent with Yamamoto *et al.* (1995), who previously examined elevation, inclination and slope aspect in the UT Hokkaido Forest. In this study, selection stands were mostly located between 300–600 m a.s.l., which was relatively low compared to Switzerland where selection forests are often distributed above 900 m a.s.l. (Zingg *et al.*, 1999). Mean annual temperature and precipitation are similar in both areas. In central Hokkaido, the climate on a high elevation may be too harsh to employ a selection system.

CONCLUSIONS

Natural selection forests in central Hokkaido can be characterized as contrasted with central Europe: 1) Tree dominance is relatively low, while tree density is considerably high in central Hokkaido. 2) Conifers belong to the same genera (*Abies* and *Picea*), while differences occur in major broad-leaved tree species (*Fagus* in Europe, *Tilia* in central Hokkaido). 3) An inverse J-shaped diameter distribution is maintained in both regions. 4) Selection forests were distributed on a relatively low elevation in central Hokkaido.

This paper was intended to fairly represent the structure and geography of selection forests in central Hokkaido. A selection forest, however, have been changing its structure over time (O'Hara *et al.*, 2007). Thus, future research should further examine the dynamics of selection stands in order to reveal the long-term effects of selection cutting in a natural forest.

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Article

Evaluation of Landscape-level Genetic Diversity in Mixed Managed Forest in Hokkaido, Japan

Masayoshi Takahashi[*1], Gen Takao[*2, 3], Satoshi Ishibashi[*1] and Takayuki Kawahara[*1]

ABSTRACT

The aim of this research was to develop an indicator of genetic diversity for three major conifer species, *Abies sachalinensis*, *Picea jezoensis* and *Picea glehnii,* and to evaluate landscape-level genetic diversity in the Toyohira River basin, of Hokkaido, Japan. Biodiversity is a key factor for sustainable forest management and often defined at three levels, ecosystem of region, species and genes. Ecosystem and species levels of diversity can be evaluated at the landscape level based on ground survey and spatial information. On the other hand, genetic diversity at the landscape level is rather difficult to assess due to the size of the distribution area and because ground surveys and direct measurements of genetic difference are needed to clarify biogeographical characteristics. For this study, we first defined a genetically homogeneous area. We then developed a genetic diversity indicator, "number of fathers," using forest register information. Finally, we evaluated the genetic diversity in our target basin. The results show that *Abies sachalinensis* and *Picea jezoensis* were widely distributed in their own "high diversity" genetic zone, whereas the high-diversity zone for *Picea glehnii* was distributed as islands. These results reflect biogeographic characteristics and show that the developed indicator for genetic diversity is appropriate for illustrating landscape-level genetic diversity in the Toyohira River basin.

Keywords: genetic diversity, landscape genetics, number of fathers

INTRODUCTION

Biodiversity is one of the key factors in sustainable forest management and is often defined at three different levels; the ecosystem of region level, species level and genes level. Genetic diversity serves as a driving force for the adaptation, evolution, and breeding of species. Homogenization of genes sometimes causes asexualization and genetic abnormality, which increase the risk of species decline through natural disasters (Aizawa *et al.*, 2007).

Landscape genetics is one approach to understanding the influence of ecological processes (Turner *et al.*, 2001). Holderegger and Wagner (2006) defined landscape genetics as research that explicitly quantifies the effects of landscape composition, configuration, and matrix quality on gene flow. Phylogeography (Avise, 2000) is also used to quantify genetic variation in relation to ecological processes, but at a larger spatiotemporal scale than landscape genetics, making it more comparable to biogeography (Manel *et al.*, 2003).

Landscape genetics aims to improve our understanding of the interactions between landscape features and microevolutionary processes, such as gene flow, genetic drift and selection. Such study also aids in identifying cryptic boundaries, which are either breaks in the gene flow across populations without any obvious cause, or secondary contacts among previously isolated populations.

Many conservation biologists have sought to determine whatconstitutes a natural break in, or between, populations. For example, the ability to delineate evolutionary significant units,

Corresponding author: Masayoshi Takahashi
E-mail: martaka@ffpri.affrc.go.jp
[*1] Hokkaido Research Center, Forestry and Forest Products Research Institute, 7 Hitsujigaoka, Toyohira, Sapporo, Hokkaido 062-8516, Japan
[*2] Center for International Forestry Research, PO BOX 0113 BOCBD, Bogor 16000, Indonesia
[*3] Present address: Forestry and Forest Products Research Institute, 1 Matsunosato, Tsukuba, Ibaraki 305-8687 Japan

management units, or conservation units depends on detecting population subdivisions.

Following the 1992 Earth Summit, the Montréal Process Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests was initiated and this group has implemented internationally accepted criteria and indicators for the conservation and sustainable management of temperate and boreal forests. In 2007 revised criteria and indicators were released. Biodiversity is also one of seven criteria and three indicators for genetic diversity. The Montréal Process has been discussed mainly in terms of national-level criteria and indicators, such as building knowledge of landscape genetics, for example, of ecoclines and the effects of isolation by distance.

On the other hand, discussing criteria and indicators for regional and / or management unit-level genetic biodiversity is very difficult. Compared to national-level genetic diversity, clear genetic drift and cryptic boundaries are rarely found at such levels. Most of the studied regions and / or management units do not have significant difference in the context of landscape genetics. Natural resource managers, especially forest managers, must determine not only what constitutes a natural break in, or between, populations, but also how to manage genetically homogenous forests and other resources.

The objectives of this research were to develop regional indicators for genetic diversity and to evaluate regional landscape-level genetic diversity in the Toyohira River basin of Hokkaido, Japan.

MATERIALS AND METHODS

Study Area

We chose Jozankei National Forest as a research site (Fig. 1). This forest, located approximately 30 km south of Sapporo City, ranges from 550 m to 1,300 m above sea level and covers an area of about 11,000 ha (Fig. 2). It is covered by cool-temperate natural mixed forests and includes part of the Shikotsu Toya National Park. The Jozankei National Forest has been managed by selective cutting for more than 30 years, since a dense forest road network was constructed in the 1970s.

We selected three conifer species, *Abies sachalinensis, Picea jezoensis,* and *Picea glehnii,* as our target species. These three wind-pollination species are major conifer species in Hokkaido and are mainly cultivated for timber production.

Regional Indicator for Genetic Diversity

Genetic homogeneity at the regional scale

From the genetic point of view, forest management activities have to consider in genetically homogenous areas (KAWAHARA, 2006). If genetically heterogeneous areas are studied, the impact of forest management activities might differ among genetic types. In such cases, we have to identity each genetic type of tree and select suitable management activities for each type. Establishing breeding regions is one approach to establishing a genetically homogenous area. In Hokkaido, a breeding region was established for *A. sachalinensis.* KITA (2002) also noted the importance of the breeding region for *P. glehnii* in Hokkaido.

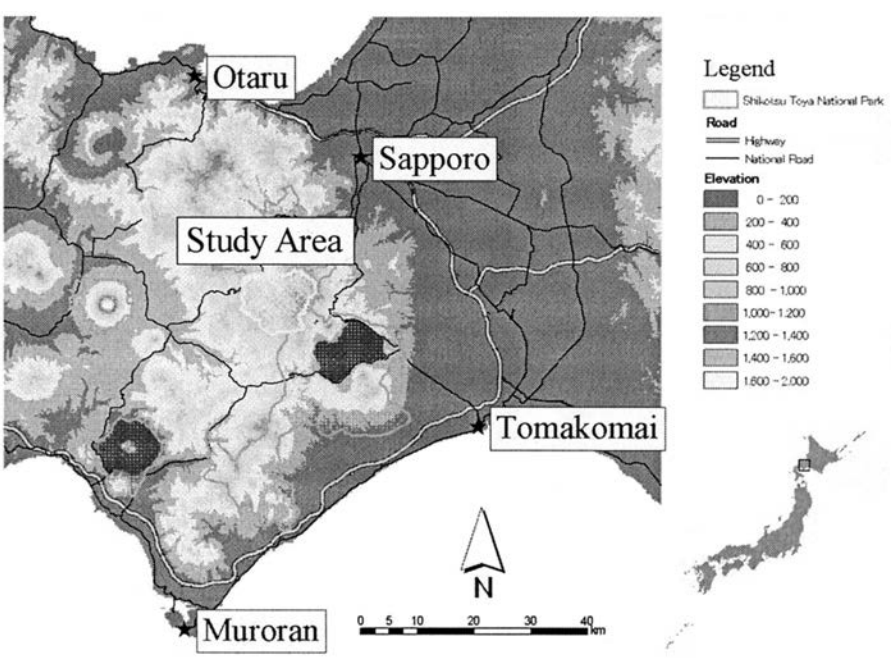

Fig. 1 Map of the research site

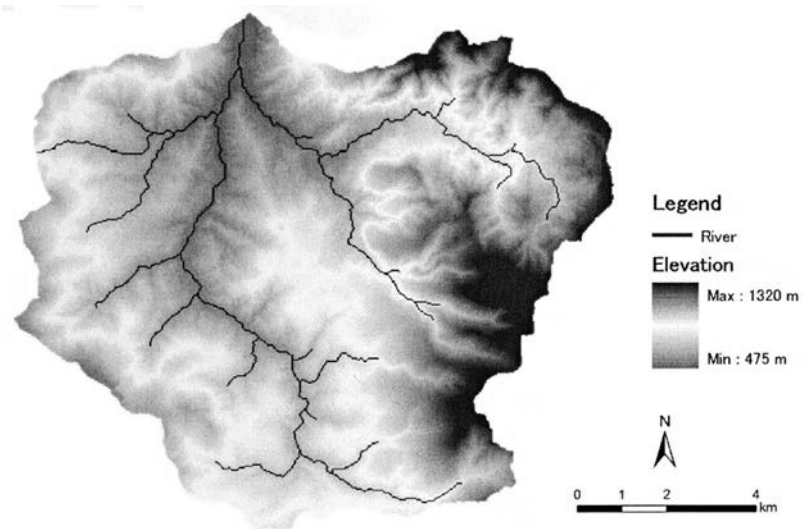

Fig. 2 Elevation and river network

Candidate indicators for genetic diversity are the criteria and indicators of THE MONTRÉAL PROCESS (2005), which include not only plant species but also vertebrates and invertebrates selected based on risks due to habitat fragmentation. However, plant species have their own biogeographic structure, and the effects of fragmentation differ in each species. For instance, the genetic diversity of Japanese beech (*Fagus crenata*) and Maries' fir (*Abies mariesii*) in fragmented areas is much higher than that in large continuous areas. Therefore, when evaluating genetic diversity in plant species, we must consider the biogeograpic structure (KAWAHARA, 2006).

KAWAHARA (2006) tried to identify genetic difference in *A. sachalinensis* in Hokkaido using random amplified polymorphic DNA (RAPD) markers. The results showed no clear differences in *A. sachalinensis* within Hokkaido, indicating that this species is genetically homogenous at the regional level. AIZAWA *et al.* (2007) conducted phylogeographical research on *P. jezoensis* using maternally inherited mitochondrial DNA and paternally inherited chloroplast DNA markers. Within Japan, they detected phylogeographically different types of *P. jezoensis* between the islands of Hokkaido and Honshu. In contrast, minor differences were found within Hokkaido; thus, *P. jezoensis* can be considered genetically homogeneous in Hokkaido. Unfortunately, we could not find any previous studies that directly measured genetic difference for *P. glehnii.* However, based on earlier breeding research, we expect that *P. glehnii* is also genetically homogenous within Hokkaido.

On the basis of the above findings, we assumed that our three target species were genetically homogeneous, at least at the river-basin scale, in the study area.

Indicator for genetic diversity in a genetically homogenous area

Within a genetically homogenous area, the effective number of fathers is known to correlate with the degree of genetic diversity (KAWAHARA, 2006). Thus, we assumed that the effective number of fathers is a suitable indicator for genetic diversity in a genetically homogenous area.

Estimation of the Effective Number of Fathers

It is very difficult to directly estimate the effective number of fathers. Therefore, development of an indirect method is needed. When data are available on the stem number per hectare in a forest compartment D, together with the area ratio R and the mixture ratio M of the species in the forest compartment derived from forest register information, the number of fathers per hectare N can be estimated indirectly as follows:

$$N = E\ D\ R\ M$$

where E is the mature ratio; that reflect the ratio of mature individuals able to produce male flowers. Unfortunately, because no information about the maturity of the stands was available, we had to estimate E from other relevant information. Age is a suitable index to show the maturity of individual trees. However, our study site has been managed by selective cutting for more than 30 years; thus, most of the stands might be of uneven age. For selective cutting stands, we considered that average height (h, m) would serve as an alternative index. In our study area, size-related information, such as average diameter at breast height (DBH, cm), is compiled in the forest register system. We thus estimated h from DBH derived from the forest register information, and the DBH – height curve was estimated from ground survey data following NÄSLUND (NAGUMO and MINOWA, 1990). While selective cutting stands could be managed theoretically, individual tree size ranged widely, and mature individuals able to produce male flowers were limited. Therefore, we hypothesized a mature ratio E of up to 0.3.

Our study site also includes other forest types, such as

alpine vegetation, and forest damaged by typhoon. Therefore, when the average height h was less than or equal to 9 m, we assumed that the mature ratio E was 0. When h was between 9 m to 15 m, we assumed that E is gradually increased from 0 to 0.3 according to the linear function below:

$$\begin{cases} E=0 & \{h \mid h \leq 9\} \\ E=0.05h-0.45 & \{h \mid 9 < h < 15\} \\ E=0.3 & \{h \mid h \geq 15\} \end{cases}$$

Effect of Pollen Dispersal

Pollen dispersal is an important factor in gene flow in plants (Ennos, 1994; Oddou-Muratorio *et al.*, 2001). To extract the real condition of the number of fathers, we must also consider the effect of pollen dispersal, using pollen dispersal. Austerlitz *et al.* (2004) summarized and evaluated research on pollen dispersal curves. They recommend that the exponential power distribution should be used at first because it is sufficiently flexible, encompasses the normal and the exponential as degenerate spatial cases, and results in moments that are always finite. In this method, pollen dispersal probability P_{ep} is given by

$$P_{ep}(a, b; x, y)=\frac{b}{2\pi a^2 \Gamma(\frac{2}{b})} \exp\left(-\left(\frac{r}{a}\right)^b\right)$$

where $r=\sqrt{(x^2+y^2)}$ is the pollination distance and Γ is the classically defined gamma function (Abrampwotz and Stegun, 1964). Parameter b is the shape parameter, affecting the 'fatness' of the tail of the dispersal distribution, and parameter a is a scale parameter.

Parameters a and b are not known for our target species, so we assumed $a=1$, $b=2$, and $r=100$ m, based on previous studies of pollen dispersal curves (Nakanishi *et al.*, 2004; Kanazashi *et al.*, 1984; Austerlitz *et al.*, 2004).

Multiplying by N and P_{ep}, it is possible to estimate the real condition of the number of fathers distributed in certain stands. We calculated the real condition of the number of fathers for each stand, and aggregated the effective number of fathers in every 30 m cell using ESRI ArcGIS 9.0.

RESULTS AND DISCUSSION

Figures 3, 4, and 5 present maps of the number of fathers for *A. sachalinensis, P. jezoensis,* and *P. glehnii,* respectively, calculated from forest register data. Each of the maps reflects the current distribution of each species in Jozankei National forest. Figures 6, 7, and 8 are maps of the number of fathers considering pollen flow for *A. sachalinensis, P. jezoensis,* and *P. glehnii,* respectively. Considering pollen flow, each of the maps illustrates the probability of the exact number of fathers.

The maximum number of fathers considering pollen flow was 10 per cell for *A. sachalinensis,* 3.5 per cell for *P. jezoensis,* and 2.5 per cell for *P. glehnii.* In terms of number per hectare, there were 114, 39, and 28 fathers for *A. sachalinensis, P. jezoensis,* and *P. glehnii,* respectively. *A. sachalinensis* had the highest and *P. glehnii* had the lowest number of fathers.

A. sachalinensis and *P. jezoensis* were genetically diverse and distributed continuously over almost all of the study area. Father-rich patches of *A. sachalinensis* were located in the northern part of the study area along the river that runs from south to north. Father-rich patches of *P. jezoensis* were mainly located in the middle part of the study site at an average elevation that seemed to be much higher than the father-rich area of *A. sachalinensis.* Father-rich patches of both species had a mosaic-like distribution.

In contrast, father patches of *P. glehnii* patches were distributed as islands. Furthermore, the average number of fathers considering pollen flow of *P. glehnii* was clearly small compared to *A. sachalinensis* and *P. jezoensis.* Natural populations of *A. sachalinensis* and *P. glehnii* reach up to 1650 m above sea level, and *P. jezoensis* reaches to 1,700 m (Hoppo Ringyo Kai, 1982). The Ecology Discource Group (1968) compared the medians of distributions, although there were very few differences, and noted that *A. sachalinensis* had the lowest elevation distribution while *P. glehnii* had the highest. In Jozankei National Forest, Ishihara *et al.* (2000) found that conifers had a very high appearance ratio between 600 and 900 m, but were not found above 1,000 m. In addition, *A. sachalinensis* was predominant in areas below 700 m and/or on southwestern slopes, while *P. jezoensis* was dominant in comparatively higher areas. Moreover, in the study area, *P. jezoensis* is located in cool spots; Izariiri-Heide, one of the distribution patches, is a well-known cool spot in the study area. Saito *et al.* (1993) investigated the vegetation at cool spot sites and reported that *P. glehnii* occupied areas surrounding such sites. They also noted that the vegetation surrounding the cool spots was clearly different and phytosociologically unique.

For each species, the distribution characteristics of number of fathers matched and reflected the species natural distribution characteristics.

In addition, none of the species showed a uniform distribution of fathers; rather, the distributions had mosaic-like patterns with "father rich" patches. The Jozankei National Forest has been managed by selective cutting for more than 30 years, which allows for a portion of the trees to be harvested at a given rotation age and creates variety in the forest structure. From a spatial point of view, the forest appears as a mosaic. Thus, we thought that management activities would be one reason for the mosaic distribution patterns on number of fathers.

We evaluated the numbers of fathers in each 30 × 30-m cell. It was then possible to analyze the results using various management units such as watershed, compartment, and/or sub compartment units. Aggregate analysis might not only provide useful information about the current situation of genetic diversity but also enhance biodiversity sound management approaches, by aiding in the selection of suitable trees to harvest

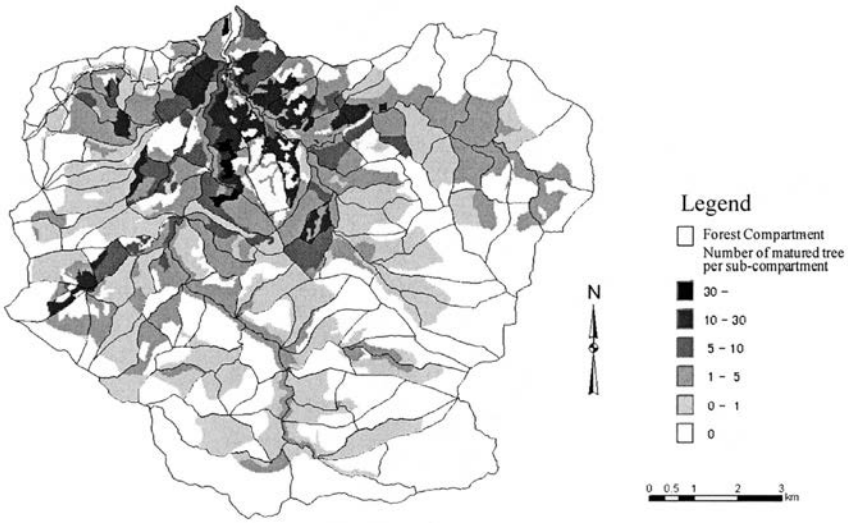

Fig. 3 Number of fathers of *Abies sachalinensis*

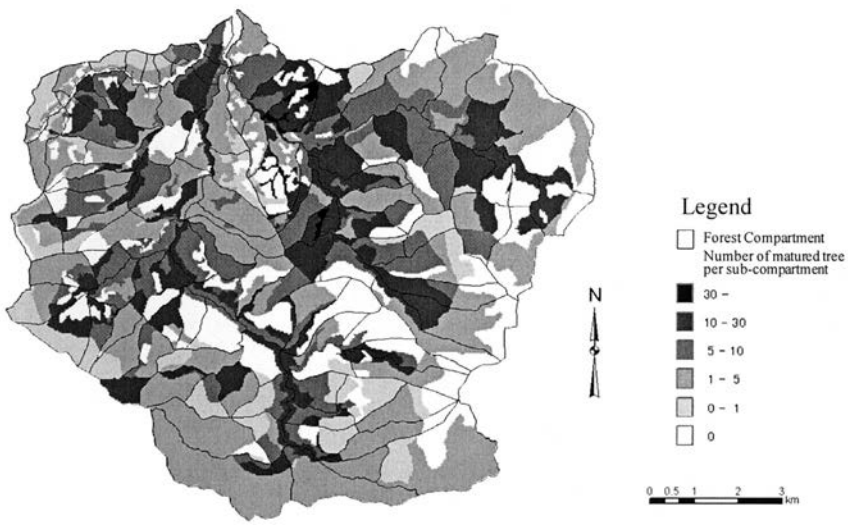

Fig. 4 Number of fathers of *Picea jezoensis*

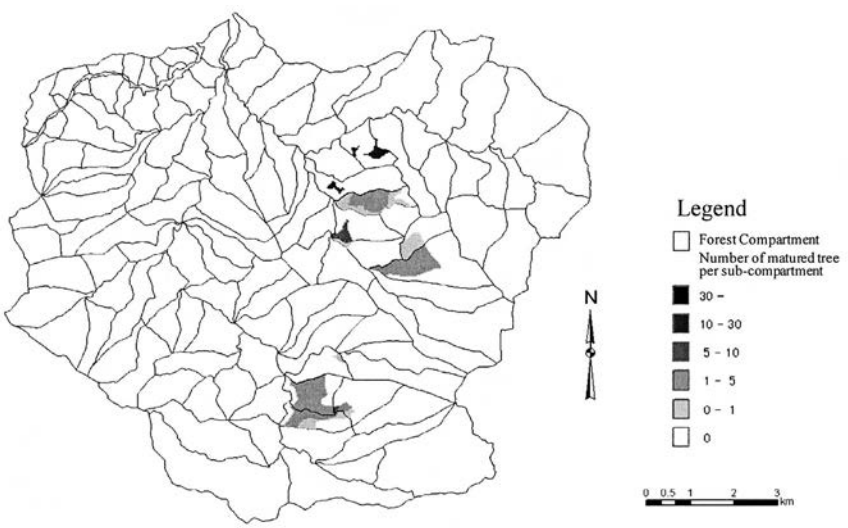

Fig. 5 Number of fathers of *Picea glehnii*

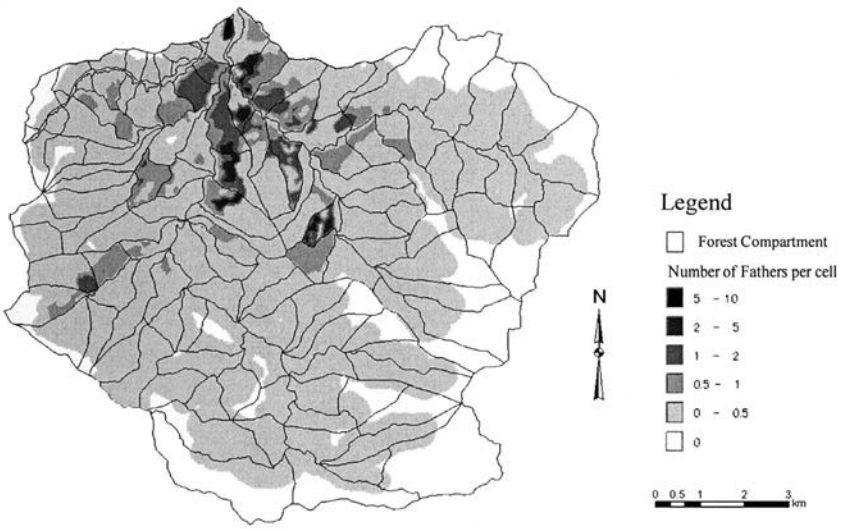

Fig. 6 Number of fathers of *Abies sachalinensis* considering pollen flow

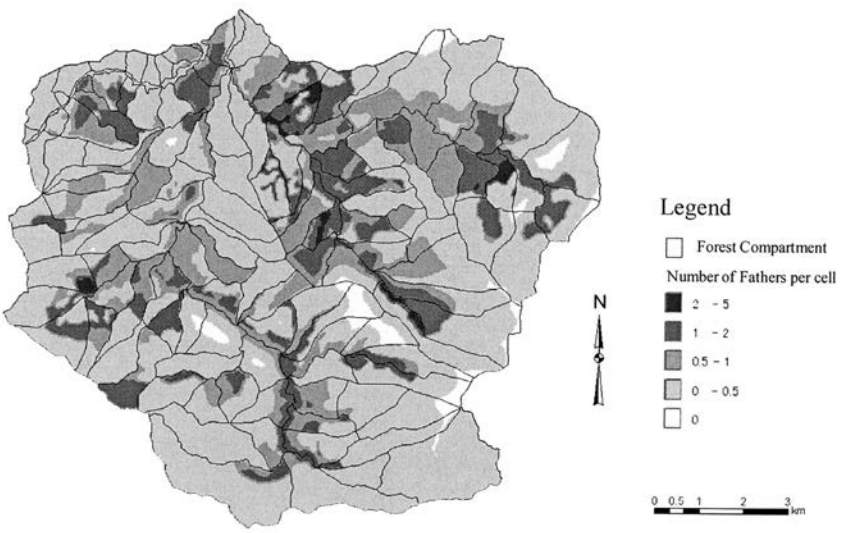

Fig. 7 Number of fathers of *Picea jezoensis* considering pollen flow

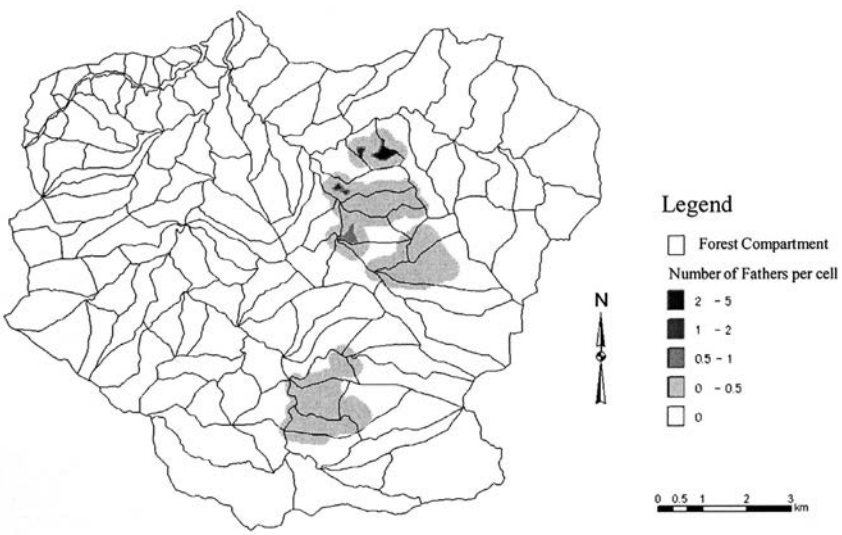

Fig. 8 Number of fathers of *Picea glehnii* considering pollen flow

and for strategic seed collection for seedling production. However, before undertaking these steps, further consideration of the methodology and verification of the results are needed.

For example, we made some assumptions when estimating the mature ratio. As our study site has been managed by selective cutting, we assumed that the maximum percentage of mature trees was 30 %, but data are needs to validate and evaluate this assumption. If a stand is managed in another way, such as by clear cutting, the maximum rate might differ from that in our case.

We also set important parameters of the pollen flow model with assumptions based on a short-distance "thin-tailed" model. Some earlier studies of pollen flow, especially long-distance distribution studies have indicated that long distance pollen flow is sometimes important when considering genetic diversity. We might need to compare both "thin-tailed" and "fat-tailed" pollen flow models. Wind direction and intensity are also important for understanding pollen flow. However, because of the lack of data for modeling wind direction and intensity, and limitations in directly measured DNA data, it was impossible to thoroughly consider all of the relevant variables within the study site.

We used forest register data for estimating the number of fathers. However, some important parameters such as average tree height and density might also be useful and could be collected from other sources, such as by remote sensing.

CONCLUSION

Number of fathers is a suitable indicator for genetic diversity if the target species are genetically heterogeneous. In Jozankei National Forest, direct genetic measurements showed that *A. sachalinensis, P. jezoensis,* and *P. glehnii* were wind pollinated and genetically homogeneous. Therefore, our proposed indicator would be effective, and we calculated it using forest register information and pollen dispersal curves.

Genetic characteristics of the species were obtained. *A. sachalinensis* and *P. jezoensis* were genetically diverse and continuously distributed. On the other hand, *P. glehnii* distributed as islands. The high genetic area of *A. sachalinensis* was located at lower than that of *P. jezoensis.*

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Article

The Influence of Forest Boundary Shape and Environmental Variables on Farmland Invasion by Wild Japanese Macaques

Shota Mochizuki[*1] and Takuhiko Murakami[*2]

ABSTRACT

Crop damage caused by wildlife, including macaques, has become an increasingly serious problem in Japan. We focused on two Japanese macaque troops with adjacent home ranges. We calculated landscape indices of their habitats and measured differences in frequency of farmland invasion between the troops. Our objective was to determine the relationship between troop invasion frequency and landscape indices (size, shape, and configuration). Location data of the "Yonekura" and "Otsuki" troops were collected by radio telemetry from 2004 to 2006. The home range areas of the two troops were estimated using the Minimum Convex Polygon method. A land-cover map was acquired from remotely sensed imagery (ALOS/AVNIR-2). This map was classified into five landscape classes (forest, farmland, urban, grassland, and water). Troop home range areas were overlain on the land-cover map, and landscape patches included in home ranges were counted. To discern differences between troop habitats, the landscape index of each patch was calculated. Size, shape, and configuration of habitat were selected according to a previous study. A generalized linear mixed model was applied to identify environmental factors contributing to farmland invasion by the troops. We calculated the importance of the variables that contributed most to farmland invasion. The home range area of the Otsuki troop was larger than that of the Yonekura troop, and within the ranges, the ratio of farmland to home range and the ratio of urban land to home range were higher for the Otsuki troop. For each landscape index, a difference was found between the habitats of the two troops. In models of the two troops, distance between farmland and forest boundary and distance from a road were important factors. Moreover, the frequency of farmland invasion differed in distances from exclosure fences. Differences in farmland invasion between troops were attributable to differences in habitat landscape indices. The shape of the Otsuki troop habitat was relatively complex, increasing opportunities for macaques to come in contact with farmland. Our results show that it will become increasingly easy for Otsuki troop to invade farmland.

Keywords: crop damage, forest boundary, generalized linear mixed model, Japanese macaque, landscape indices

INTRODUCTION

Recently, crop damage caused by wildlife has become a serious problem in Japan (MIURA, 1999; 2008). To develop an appropriate relationship between people and wildlife, it is important to have an understanding of wildlife behavior and to develop appropriate technologies and management methods. Crop damage by Japanese macaques (*Macaca fuscata*) is remarkable, amounting to 40 million yen in Niigata Prefecture. This accounts for 47% of all wildlife damage costs in the prefecture. Solutions to such losses should be developed within the context of a harmonious relationship between humans and wildlife. Japanese macaques generally live in forests (KOGANEZAWA, 1991), and crop damage is elevated in farmland bordered by woodlands (SPRAGUE, 2007). Crop damage by

Corresponding author: Shota Mochizuki
E-mail: f10n001e@mail.cc.niigata-u.ac.jp
[*1] Graduate School of Science and Technology, Niigata University, 8050, Ikarashi2-no-cho, Nishi-ku, Niigata, 950-2181, Japan
[*2] Faculty of Agriculture, Niigata University, 8050, Ikarashi2-no-cho, Nishi-ku, Niigata, 950-2181, Japan

macaques differs among troops and environments (SUZUKI, 2003). Therefore, development of appropriate management guidelines is dependent on an understanding of macaque behavior within a range of habitat types.

Driving macaques away from the farmland has been used as a technique to limit crop damage. However, the effect of this technique is not consistent with crop damage due to variations in macaque home ranges, land usage, and regional environments. CONOVER (2002) demonstrated the importance of manipulating habitat to reduce damage. However, before doing so, it is necessary to evaluate damage-related environmental factors (HONDA *et al.*, 2009). Existing reports give accounts of the relationship between habitat configuration and crop damage (NAUGHTON-TREVES *et al.*, 1998; HILL, 2000; SAJ *et al.*, 2001; IWASAKI and SPRAGUE, 2005). However, the spatial patterns of habitats (*e.g.,* size and shape) have been little studied. Selected landscape indices have been used to quantify habitat spatial patterns, and this procedure has been applied to wildlife conservation planning. A specific conservation plan is initiated by capturing habitat patterns as defined by landscape indices such as size, shape and configuration (MCGARIGAL and MCCOMB, 1995; HANSEN *et al.*, 2001; GRAY *et al.*, 2004). Therefore, it is also important to examine the relationships between habitat landscape indices and crop damage caused by wildlife.

The behavior of macaques is quite varied and depends on home range, human land use, and regional environment; the extent of crop damage is also varied. As a starting point, it is necessary to describe the behavior of wild macaque troops in a range of environments. Reports on macaque troop behavior are available, as they are measurements of the amount of damage they inflict on crops (SUZUKI, 2003; ENARI *et al.*, 2005; YOSHIDA *et al.*, 2006). However, descriptions of ecological differences among troops are few. For managing crop damage, it is essential to focus on differences between troops.

We examined two macaque troops with adjacent home ranges. To evaluate differences in habitats, landscape indices (*i.e.,* size, shape, and configuration) were calculated. We also examined differences in farmland invasion between the two troops. Our primary objective was to determine the relationship between troop behaviors and landscape indices, with the ultimate aim of controlling crop damage through management of macaque habitat.

Study Area

The study area was Shibata City, Niigata Prefecture (37°57′ N, 139°19′E, 532 km^2, Fig. 1). The elevation ranged from -19 to 1496m above sea level, and forests cover 64% of ground area. Crops in this region have been damaged by macaques since 1983, and the area affected has expanded gradually. An investigation in Shibata City revealed 14–17 troops that included a total of up to 700–800 individuals. The intensity of crop dam-

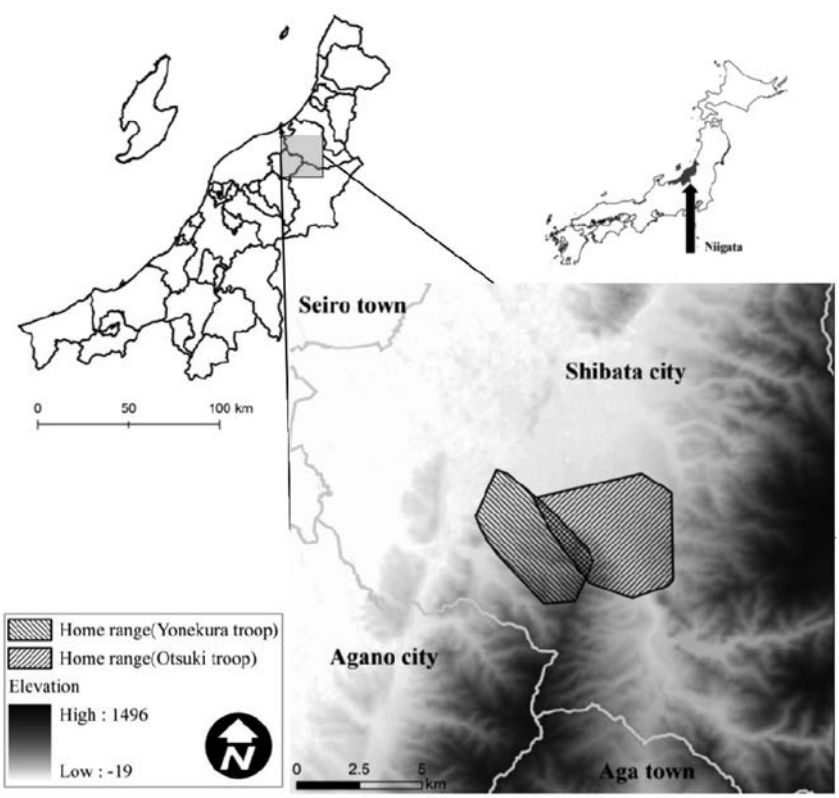

Fig. 1 Location of study area and home range of macaque troops

age is increasing, and the risk of life-threatening injuries through home invasion has become a concern. Annual crop damage costs approach 15 million yen on average, with yearly fluctuations. Hunting has been used as a remedial measure, which exterminated about 100 monkeys each year. However, hunters have now taken the lead in driving macaques away from farmland, usually from June to November, the period of the most intense crop damage.

Materials

We studied the "Yonekura" and "Otsuki" troops using data acquired by hunters during 2004–2006 (Fig. 2). The information gathered includes location data obtained by radio telemetry, a method widely used for tracking wildlife. The location data are acquired by attaching the transmitter to wildlife, and the signal is received by a Yagi antenna and receiver. The antennae have strong directionality and are often used on animals whose native habitat makes direct observation difficult (White and Garrot, 1990). In total, location data were collected for 207 and 249 points of the Yonekura and Otsuki troops, respectively. We used LT-01 (CIRCUIT DESIGN, Inc.) transmitters and IC-R20 (ICOM, Inc.) receivers.

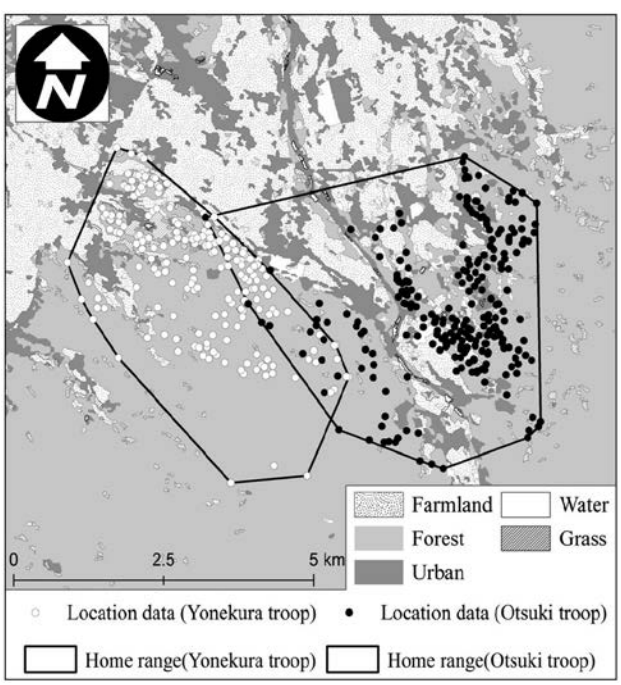

Fig. 2 Landcover map classified using ALOS/AVNIR-2 and home range area of Yonekura troop and Otsuki troop determined by using Minimum Convex Polygon method
Each patch was classified into five classes (Farmland, Forest, Urban, Water and Grassland).

METHODS

Calculation of Landscape Indices

The locations of the macaques were visualized using Geographical Information System (GIS) software (ArcGIS 9.2; Environmental Systems Research Institute, Inc.). The home range areas of the two troops were determined using the Minimum Convex Polygon method (MCP). MCP is a method for constructing a polygon that connects boundary location points defining home range areas. Although home range size may be overestimated, MCP is a simple and easy method (Ozaki and Kudo, 2002; Saeki and Waseda, 2006) that allowed us to compare the troops.

Land cover was classified using ERDAS IMAGINE 9.2 software (Leica Geosystems, Inc.) to plot landscape composition of the study area. The satellite images used (ALOS/AVNIR-2 image) were captured on 27 February in 2006, 27 May in 2006, and 12 August in 2007. The data were orthorectified with a digital elevation model. All satellite data were geo-coordinated to the Universal Transverse Mercator system. Shade caused by topographic relief can create serious obstacles to analysis of remote sensing data. We used the Minneart topographic correction method to offset topographic effects (Murakami, 2007). Moreover, to correct for the influence of atmosphere between seasons, we matched a digital number using a pseudo invariant target (Hall *et al.*, 1991; Schroeder *et al.*, 2006) between sets of satellite data (Awaya and Tanaka, 1999). For accurate classification, we prepared multi-temporal normalized difference vegetation index (NDVI, Myneri and Asrar, 1994) composite images. We applied supervised classification to the composite images (Murakami *et al.*, 2001). NDVI was calculated from the ALOS/AVNIR-2 data captured a three different times. It is defined as

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

where *RED* and *NIR* are the visible red and near-infrared reflectance factors, respectively. We postulated that forest, urban land, and farmland could be classified accurately by stacking NDVI images from February, May, and August. The land-cover map was classified from NDVI composite images by supervised classification with maximum likelihood. Patches of land cover were classified into five categories (*i.e.,* forest, farmland, urban, grass, and water) (Fig. 2). The landscape map kappa coefficient (representing classification accuracy) was 0.82.

The home range plots of the two troops were overlain on the land-cover map (Fig. 2), and the patches including the home range were counted. To compare habitat differences between troops, we calculated the landscape index of each patch using FRAGSTATS 3.3 (McGarigal and Marks, 1995). Indices calculated by this software are classified according to five dimensions (*i.e.,* size, shape, core area, diversity, and configuration). We selected habitat size, shape, and configuration based

on previous studies (HANSEN *et al.*, 2001; HERZOG *et al.*, 2001; GRAY *et al.*, 2004) that quantified landscape structure in a variety of ecosystems and examined the relationship between landscape structure and landscape function. We applied five landscape metrics: Large Patch Index (LPI), Mean Patch Size (MPS), Landscape Shape Index (LSI), Area-Weighted Mean Shape Index (AWMSI) and Interspersion and Juxtaposition Index (IJI) (Table 1). For the analysis, we chose forest patches within macaque habitat, urban patches that are risk factors for macaques, and farmland patches that are food resources for macaques.

Relationship between Farmland Invasion and Environmental Factors

To determine environmental characteristics of farmland invasion, we compared points where farmland was invaded with points where farmland was not invaded. The macaque location data were overlain on the land-cover map. We defined the macaque locations on the farm land as "farmland invasion". Some artifact is possible in these location points because radio telemetry data may produce sampling bias when the tracking duration is long (PALOMARES and DELIBES, 1992; REVILLA *et al.*, 2000). In our study, sampling bias was small because we used data from 3 years. Of the samples with farmland invasion, 22 were from the Yonekura troop and 46 were from the Otsuki troop. We applied a random-variate generation method in GIS to randomly generate the same number of points in the farm land. This sample of points was classified as "no farmland invasion." To improve the reliability of the data, the "no farmland invasion" points that exist within 200m of the "farmland invasion" points were excluded, as 200m is the average distance that a macaque moves in about an hour (SUZUKI, 2003). Total sample sizes for "farmland invasion" and "no farmland invasion" categories combined were 44 and 92 for the Yonekura and Otsuki troops, respectively (Figs. 3 and 4).

Each environmental factor (topography and human disturbance) was selected from previous research and calculations were made using GIS (Table 2). To control for confounding factors, topography and human disturbance factors were validated (ROTHMAN, 2002). Distance from forest boundary was selected as topographic factor. NAUGHTON-TREVES *et al.* (1998) and SAJ *et al.* (2001) suggested that this factor is important with regard to the extent of crop damage by wildlife. Distance from water, which WILSON *et al.* (2005) reported as a risk factor, was added. Distances from urban lands and roads were selected as human disturbance factors because these variables are be-

Table 2 List of environmental variables

Dependent variables		Independent variables	
The invasion of farmland	Presence = 1	Distance from forest boundary	X_1
	Absence = 0	Distance from road	X_2
		Distance from water	X_3
		Distance from urban	X_4
		Distance from fence	X_5

Table 1 Indices used to evaluate the difference of habitats (Yonekura troop and Otsuki troop)

Acronym	Index name (unit)	Description
LPI	Largest patch index (%)	The largest patch index indicates the share of the landscape that is occupied by the largest patch of the landscape.
MPS	Mean patch size (ha)	Mean patch size is computed by dividing the total landscape (or land-use type) area by the number of patches.
LSI	Landscape shape index	In the landscape shape index, the sum of all patch perimeters is divided by a figure equivalent to the perimeter of a circle with the same area as the landscape area. LSI increases with increasing overall complexity of patch shapes.
AWMSI	Area-weighted mean shape index	Similar to mean shape index, mean patch shape complexity; equals 1 when all patches are circular and increases as patches become non circular, but patch shape index weighted by patch area
IJI	Interspersion and juxtaposition index (%)	The interspersion and juxtaposition index is calculated from the relationship between the length of each edge type and total edge of the landscape, divided by a term based on the number of land use types. IJI approaches 0 when adjacencies are unevenly distributed; IJI = 100 if all patch types are equally adjacent to all other patch types.

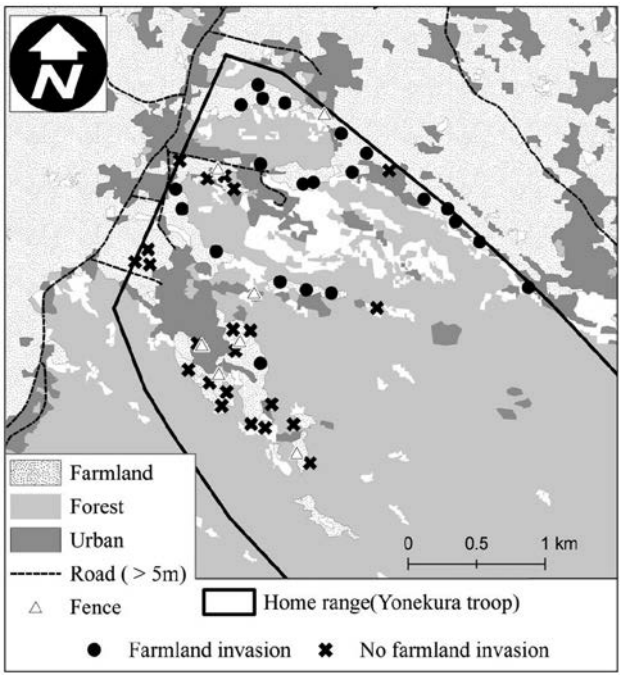

Fig.3 The invasion of farmland by Yonekura troop
Presence and absence data was applied.

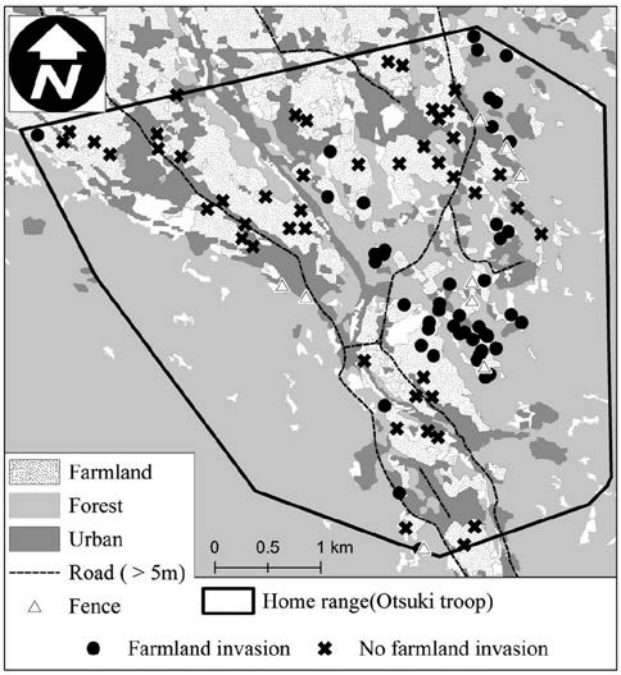

Fig. 4 The invasion of farmland by Otsuki troop
Presence and absence data was applied.

lieved to be risk factors for macaques. Distance from farmland bounded by exclusion devices such as electric fences (hereafter, distance from fence) was selected for inclusion. We used the land-cover map to calculate the distance from forest boundary, water, and urban lands. To calculate the distance from roads (only roads > 5m wide were used), a 1 : 25,000 digital map spatial-data framework (Geographical Survey Institute) was used. The position of the fenced farmland was recorded using GPS (GPSMAP60Cx ; Garmin, Inc.) in the field survey.

Statistical Analysis: Generalized Linear Mixed Model

To examine the relationships between farmland invasion and each environmental factor, we used a generalized linear mixed model (GLMM: Faraway, 2006; binomial error structure, logit link function) because this method controls for confounding factors (Rothman, 2002) and allows for spatial autocorrelation between neighboring sub-compartments (Crawley, 2005). The dependent variable was presence or absence of invasion, and five independent variables were considered as candidate environmental factors. The point numbers of the location data were applied as random effects. Unobservable effects thought to influence the model were treated as random effects (Crawley, 2005). In this analysis, it becomes possible by applying point numbers as random effects to treat each location data as independent.

To calculate the importance of variables (IOV), the model-averaging method was employed. The model-averaging method was applied instead of model selection techniques because the former allows for unbiased and robust parameter estimation (Johnson and Omland, 2004). IOV ranged from 0 to 1, and more important variables were given larger values. We tested for collinearity among variables using the variance inflation factor (VIF), where VIF > 10 denotes multi-collinearity (Robert and O'Brien, 2007). Model accuracy was determined by comparing observed and predicted data. To calculate overall accuracy, the cut-off point was set to 50%. The cut-off point of 50% was most often applied in model accuracy evaluation (Hosmer and Lemeshow, 2000). Analyses were performed using R ver.2.8.1 (R Development Core Team, 2008).

RESULTS

Differences between Macaque Habitats

Table 3 shows landscape indices for forest, urban land, and farmland for each troop. LPI and MPS (index of patch size) values were high in the Yonekura troop forest land, whereas urban land and farmland in the Otsuki troop habitat showed high values. These results indicated that the forest patch used by the Yonekura troop is rather more clumped than is that of the Otsuki troop. LSI and AWMSI (index of the patch shape) showed high values for forest, urban land, and farmland in the Otsuki troop habitat. These results indicated that the habitat of the Otsuki troop has a complex shape. IJI, the index of patch configuration, had low values in the Otsuki troop farmland. The

Table 3 Comparison of landscape indices (Yonekura troop and Otsuki troop)

	Forest		Urban		Farmland	
	Yonekura	Otsuki	Yonekura	Otsuki	Yonekura	Otsuki
LPI (%)	82.60	27.87	2.48	9.40	2.23	4.33
MPS (ha)	74.33	30.07	2.05	4.73	5.95	9.05
LSI	5.54	11.20	9.00	15.91	7.59	13.86
AWMSI	4.29	6.08	3.08	6.12	2.88	3.98
IJI (%)	74.93	74.78	55.90	52.22	61.89	43.26

Table 4 Model of the invasion to farmland by Yonekura troop

	Model averaged estimate	Standard error	IOV	*p*-value	VIF
Intercept	1.442	1.769	–	0.415	–
X_1	−0.019	0.008	0.940	0.012	1.830
X_2	0.002	0.001	0.860	0.045	1.390
X_3	−0.001	0.001	0.430	0.494	1.810
X_4	0.004	0.006	0.490	0.450	1.820
X_5	0.003	0.002	0.900	0.020	2.010

Environmental factors affecting invasion of farmland were analyzed.

Table 5 Model of the invasion to farmland by Otsuki troop

	Model averaged estimate	Standard error	IOV	*p*-value	VIF
Intercept	1.031	1.042	–	0.322	–
X_1	−0.018	0.009	1.000	0.004	1.230
X_2	0.004	0.002	0.840	0.043	1.410
X_3	0.000	0.001	0.230	0.832	1.420
X_4	0.007	0.006	0.540	0.254	1.380
X_5	−0.002	0.001	0.860	0.042	1.380

Environmental factors affecting invasion of farmland were analyzed.

Table 6 Classification accuracy of prediction models

Yonekuta troop					Otsuki troop				
		Observed					Observed		
		Invade presence	Invade absence	Total			Invade presence	Invade absence	Total
Predicted	Invade presence	19	3	22	Predicted	Invade presence	40	6	46
	Invade absence	4	18	22		Invade absence	8	38	46
	Total	23	21	44		Total	48	44	92

In Yonekura troop, sensitivity = 82.6% (19/23); specificity = 85.7% (18/21); overall accuracy = 84.1% (37/44). In Otsuki troop, sensitivity = 83.3% (40/48); specificity = 86.3% (38/44); overall accuracy = 84.7% (78/92).

value of IJI (index of patch configuration) was low in the farmland of the Otsuki troop. This result indicate that farmland in the Otsuki troop habitat had a connected structure.

Difference between Troops

The estimated relationships between the invasion of farmland and environmental factors are presented in Tables 4 and 5. In these models, distance from forest boundaries and roads affected both troops in the same manner. Distance from forest boundary was an important factor for macaque invasion of farmland. Moreover, distance from roads was a contributory risk factor for both troops, suggesting they invade farmland that is near the forest boundary and far from any roads. The effect of distance from a fence differed between troops. For the Yonekura troop, the value was positive, indicating that the distance from fences influenced the risk of invasion. The value was negative for the Otsuki troop, indicating that the distance from fences did not influence the likelihood of invasion. The Otsuki troop invades fenced farmland, whereas the Yonekura troop tends to avoid fenced farmland. Other factors were of low importance (< 0.8) and therefore did not significantly affect farmland invasion. Maximum VIF of the integrated model was low. For the Yonekura and Otsuki troop models, VIF were 2.49 and 3.45 (< 10), respectively, indicating no multi-collinearity. The model classifications were calculated comparing the predictive models and observed data (Table 6). The overall model accuracies were 84% and 85% for the Yonekura and Otsuki troops, respectively.

DISCUSSION

From comparison of landscape index (Table 3), the habitat of the Yonekura troop is well forested, and the habitat shape is simple. The habitat of the Otsuki troop covered large tracts of urban land and farmland, the habitat shape was complex, and the farmland had a connected structure. By this difference, it is thought that the dependence to farmland changes in both troops. Since large tract of urban land and farmland exists compared with Yonekura troop in the habitat of Otsuki troop, the dependence to farmland may be high. Moreover, probably, it is related to ease of farmland invasion that the forest boundary shape is also complicated.

GLMM demonstrated that environmental factors affecting farmland invasion were distance from the forest boundary, distance from roads, and distance from fences (Table 4 and 5). The importance of forest boundary corroborates results of Naughton-Treves *et al.* (1998) and Saj *et al.* (2000). The distance from road was risk factor for both troops and it supports that wildlife does not use human activity area (Mochizuki *et al.*, 2009; Yamada and Muroyama, 2010). Although there was no effect of fences at Otsuki troop, it was effective in Yonekura troop. This indicates the effect of fences is case by case. Fences can be effective if they are properly maintained. About the effect of fences, the habituation to farmland may be related ineffective at Otsuki troop. Moreover, attractive food may exist in the farmland surrounded on the fence. The results of GLMM indicate the Yonekura troop appears to invade farmland near to the forest boundary and far from roads and fences. The Otsuki troop appears invade farmland far from roads and near the forest boundary and fences. The classification accuracies of the models were high, indicating they are adequate for practical purposes.

The difference between troop behaviors likely relates to habitat differences, which are clearly shown in the landscape indices. In particular, the forest boundary shape and habitat configuration are important. Conover (2002) and Grey *et al.* (2004) suggested a relationship between behavior and the farmland/forest boundary. The Otsuki troop habitat encompassed large areas of farmland, which is easily invaded because of the complex shape of the forest boundary. Moreover, farmlands within the range of the Otsuki troop have a connected structure, allowing macaque easy access to resources across adjacent farms. Enari *et al.* (2005) suggested that a foraging strategy that combines farm products with natural food sources provides a steady food supply through the year. A troop that applies this strategy will undergo rapid population growth. Taming wild animals by feeding them also contributes to farmland invasion. One likely reason for the ineffectiveness of farm fencing in reducing Otsuki troop invasion is that high population growth (fuelled by farm food) forces the animals to forage outside their natural habitat. Even when troop home ranges are adjacent, we believe habitat differences can account for behavioral differences.

In conclusion, we propose management of the distance between forest boundary and farmland as a means of controlling damage. Clearly, farms close to forest are at high risk from our models. Conover (2002) demonstrated that wildlife damage is controlled by managing the configuration of urban land, farmland, and forest on large scales. The insertion of buffer zone between farmland and forest can reduce damage (The Ministry of Agriculture, Forestry and Fisheries, 2007). It is possible to extend the distance between farmland and forest by intension of buffer zone. In addition, installation of the artificial thing (*e.g.,* road, human settlement) is also important. It is reported that wild animals dislike the place with human activities (Mochizuki *et al.*, 2009; Yamada and Muroyama, 2010). In our models, the distance from road was risk factor for macaque troops. The result of the models also supports these reports. To reduce crop damage by Japanese macaques, the management of land use is required. Moreover, the spatial configuration of farmland and the shape of the forest boundary should be managed, as these both affect the invisibility of farmland. Since only two Japanese macaque troops are treating in this study, quantification is difficult, but the spatial configuration and patch shape is also important for the management of crop damage.

Finally, it will be necessary to increase the generalizability

of our findings by studies that include more than two troops of macaques. In addition, the similar investigations that treat landscape index and environmental variables are required not only about Japanese macaques but also other wild animals (*e.g.,* wild boar [*Sus Scrofa*], sika deer [*Cervus nippon*], Asiatic black bears [*Ursus thibetanus*]).

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Article

The Effect of Simultaneous Harvesting of Adjacent Plantation Stands on Acceptable Cutting Age

Keisuke Toyama[*1, 2]

ABSTRACT

Using the standard parameters of stand and logging conditions and incorporating cost reductions and discount rates, I estimated the financial yield under the soil-rent theory, present value of future profit (PVFP) model, and forest-rent theory. I observed the effects of cost-cuttings on shifts in the optimal cutting age and the range of acceptable cutting age caused by the simultaneous harvesting of adjacent conifer plantation stands in Japan. Under the forest-rent theory, the optimal cutting age was 110 years, which was the upper limit of the calculation. The lower limit of the range of acceptable cutting age was greater than 100 years under all assumptions. With simultaneous harvesting, the optimal cutting ages under all assumptions were within the acceptable ranges, and the acceptable range could be narrowed for PVFP. Shifts in the optimal cutting ages resulting from simultaneous harvesting were small compared to those caused by changing the discount rate and the rate of subsidies for planting and silvicultural operations. These results indicate that forest managers can decide on cutting age without being concerned about the dispersal of the current stand ages and the optimal cutting ages of adjacent stands.

Keywords: cutting age, simultaneous harvesting, clear-cutting, conifer plantation

INTRODUCTION

In Japan, private forests are often spatially scattered and relatively small, and policies which aim at the cooperation among private forest managements and promote treatments such as thinning in young small-scale private forests to keep them in good condition, are highly promoted. In addition, through thinning, large forests are expected to meet the requirements of a properly managed forest or a carbon sink, as defined by the Kyoto Protocol. Conversely, although clear-cutting is not actively conducted in every region of Japan, many cases exist in which adjacent private forest stands are simultaneously clear-cut, and in some regions, the frequent development of large clear-cut stands has led to concern regarding the degradation of social benefits that forests are expected to provide for.

Simultaneous harvesting (commercial thinning and clear-cutting) of adjacent private forest stands can decrease logging costs, and by temporally and spatially controlling the dynamics of forest patches, it might improve social benefits such as biodiversity (Bettinger and Johnson, 2003). However, some problems are inherent in such an approach, such as the disregard for optimal cutting age, the inequality of the cost reductions among adjacent forest owners, and a reduction in the number of small forest patches.

I evaluated shifts in optimal cutting age brought about by simultaneous harvesting in clear-cutting forestry at Japanese conifer forest, under many combinations of parameters and examined the extent of the shifts by determining whether they are within the ranges of acceptable cutting age. I also assessed possible economic losses caused by simultaneous har-

Corresponding author: Keisuke Toyama
E-mail: toyama310@fr. a. u-tokyo. ac. jp
[*1] Graduate School of Agricultural and Life Sciences, the University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-8657, Japan
[*2] Research Fellow of the Japan Society for the Promotion of Science

vesting, such as those resulting from having to harvest a stand that is not of optimal cutting age. JOHANSON and LÖFGREN (1985) and AKAO and ARIKI (1989) reported the relationships between optimal cutting age and each parameter of the soil-rent theory, and suggested that increasing standing tree price reduces the optimal cutting age. This suggests that cost cutting in logging might act similarly, but the extent of the effect is not known. The effects of each parameter related to simultaneous harvesting on optimal cutting age and the ranges of acceptable cutting age were also examined by observing an output under each combination of parameters.

MATERIALS AND METHODS

Evaluation of Discounted and Undiscounted Cash Flow

To evaluate the profitability of forestry and to determine the optimal cutting age, I used three methods of calculating discounted and undiscounted cash flow. In the considerations that follow, in accordance with custom (e.g., TANAKA, 1991; EJIRI, 1993), I assumed no monetary inflation and no change in yield or in cost parameters such as labor cost per man-day.

Soil expectation value (SEV) under the soil-rent theory

The soil rent theory assumes an initial condition of bare land under the theory of soil expectation value. That is, all incomes and outcomes of a perpetual series of cutting rotations are calculated as soil expectation value (SEV) according to FAUSTMANN's formula using a specific discount rate. About SEV, TANAKA (1991) presented some explanations and examined cases in which bare land is owned or leased separately, and plantation costs are evaluated from owned or leased capital. In this research, however, I did not consider the existence of owned capital because no difference exists between borrowed money and the opportunity cost of owned capital if we assume that the interest rate for borrowed money and that for the investment of owned capital are the same. Thus, I used the following definition of SEV:

$$SEV = \frac{Xu - Co(1+p)^u}{(1+p)^u - 1} - \frac{(b+v)}{p}, \tag{1}$$

where u is cutting age, Xu is the present value at age u of economic yields (gross income minus logging costs) of commercial thinning and clear-cutting estimated from the Equation (4). The regression curve for calculating Xu is explained in the paragraph 'Calculations'. Co is the present value at age 0 of planting and silvicultural costs, p is the discount rate, b is the annual ground rent, and v is the annual management cost.

Present value of future profit (PVFP)

TANAKA (1991) defined present value of future profit (PVFP) as the present value of a perpetual series of future profits. This means that past costs (and profits, if they exist) are ignored. I applied this model to current typical private Japanese conifer plantations that were planted some decades ago because it appears that the current and future profitability of forestry, irrespective of past planting and silvicultural costs, are the current concern. Some discount rates were used to calculate both PVFP and SEV. Given that this calculation does not start from bare land but from a current forest, and that past costs are neglected, current stand condition, especially current stand age, is important for evaluating the present value of the forest. I assumed current stand ages to exist in 10-year increments between 0 years (immediately after planting) and 50 years (before commercial thinning). Although costs for some silvicultural operations are incurred in stands with young current ages, these were neglected for ease of calculation; that is, I assumed that all such costs have been paid or prepared for. For the second and subsequent rotations, the optimal cutting age for SEV was used as the cutting age. The definition of PVFP is as follows:

$$PVFP = \frac{Xu + SEVmax}{(1+p)^{u-u0}} - \frac{(b+v)}{p}\left(1 - \frac{1}{(1+p)^{u-u0}}\right), \tag{2}$$

where $SEVmax$ is the SEV when cutting age is optimal for SEV and $u0$ is the current stand age.

Annual economic yield under the forest-rent theory

The forest-rent theory assumes the existence of a series of forest stands with continuous stand ages. Under this theory, it is not necessary to take the discount rate into account because a series of stands insures continuous harvesting and silviculture within the same year without time lag. The definition of forest rent (FR) is

$$FR = \frac{Xu}{u} - (b+v) - \frac{C_0}{u}, \tag{3}$$

where discount rate is assumed to be zero.

Optimal Cutting Ages and Ranges of Acceptable Cutting Age

NOMURA (1955) reported examples for which only a small deficit was incurred when cutting ages that differed slightly from optimal were adopted, and assumed that the acceptable cutting age was one that achieved ≥90% of the maximum mean annual increment or maximum financial yield. Similarly, HIRATA and TANAKA (1984) used 95% as a threshold. These percent-based methods are useful, but one of their drawbacks is that they cannot be used when the total financial yield is below zero. Here, I regarded the near-best cutting ages as acceptable and calculated the ranges of acceptable cutting ages (acceptable ranges) that yielded ≥95% or 90% of the maximum financial yield, or equal to or more than the maximum money yield minus 50,000 or 100,000 yen/ha. Hereinafter, these are referred to as the 95%, 90%, 50,000, and 100,000 ranges (Fig.1). Note that I did not use 50,000 or 100,000 yen/ha, but rather 1,000 yen or 2,000 yen/ha for FR because the order of FR is much smaller than that of SEV and PVFP, given that financial yield

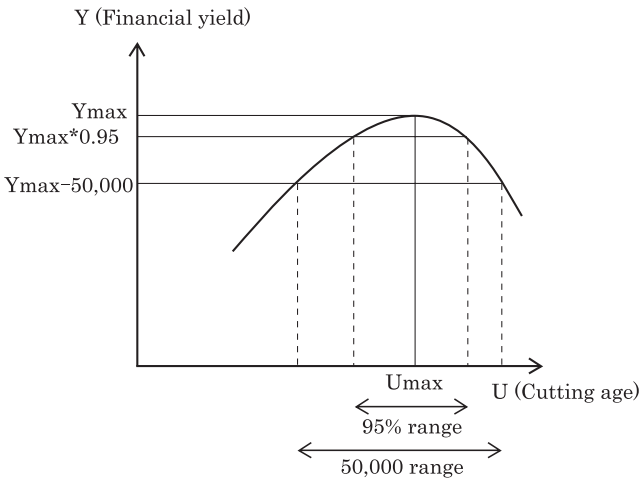

Fig. 1 Example of acceptable ranges

is divided by cutting age.

Yield Table, Thinning System and Gross Income

For the estimations of financial yield as well as logging, planting, and silvicultural costs, standard parameters for all of Japan or for Kaneyama area in the Yamagata Prefecture were used. Kaneyama area is located in the northeastern region of Japan. It experiences heavy snowfall during the winter, and sugi (*Cryptomeria japonica*) plantations in the area do not exhibit rapid declines in growth after their peak.

To prepare yield tables that can be used for assumed thinning systems, the Local Yield Table Construction System (LYCS) (NAKAJIMA *et al.*, 2010; SHIRAISHI, 1986) was used. The assumed species was sugi, and the assumed planting density was 3000 trees/ha. In addition to cleaning, pre-commercial thinning at a stand age of 30 years, and subsequently no more than three rounds of commercial thinning of 25% of the stand at ages 50, 70, and 90 years were assumed (e.g., for the cutting age of 110 years, financial yield was calculated assuming that commercial thinning had been conduced zero to three times). An optimal thinning system was then chosen. However, it was assumed that only felling and no logging was to be conducted if this yielded a higher profit than commercial thinning because commercial thinning can lead to poor profitability even when anticipated. Mid-level site quality was assumed for all stands. Given that LYCS can generate yield tables for stand ages every 5 years up to 110 years, and that clear-cutting is unrealistic in very young stands, it was assumed that clear-cutting could be conducted in stands between 50 and 110 years of age.

Log production was estimated based on the diameter distribution and average tree height of the harvested trees derived from the yield table constructed by LYCS, and gross income was estimated by multiplying log volume and log price for each log type, given its diameter and length class. As a flexible estimation model, log prices and total gross income can be modified assuming changes in log prices. Examples of stand parameters and gross incomes corresponding to thinning systems are shown in Table 1.

Logging System

I assumed a vehicle-based logging system (i.e., yarding road construction, felling by chainsaw, prehauling by grapple loader, limbing and bucking by processor, primary transportation by forwarder, and secondary transportation by truck) exclusively because it is one of the widely-adopted logging systems in areas with relatively mild topographical conditions in Japan. The variable and fixed costs of each logging operation were calculated using standard parameters (NATIONAL FORESTRY EXTENSION ASSOCIATION IN JAPAN, 2001).

Simultaneous Harvesting of Adjacent Stands

Many economic and social benefits are brought about by cooperation among multiple forest owners (KITTREDGE, 2005), including direct economic benefits from logging (KONDOH *et al.*, 2000; TOYAMA and TATSUHARA, in press). I assumed that four operational improvements (cost reductions) can be achieved by simultaneous harvesting:

(a) Shortening the length of newly-constructed yarding roads between forest roads and harvested stands.
(b) Reducing the frequency of machine transportation into or out of harvested stands.
(c) Completing site preparation using a grapple loader just after logging, rather than by hand just before planting.
(d) Increasing annual operation rate of forestry machines by assuring loggers sustained and constant business. High annual operation rate leads to relatively low fixed costs.

Note that (a) and (b) are achieved directly by simultaneous harvesting, whereas (c) and (d) are accomplished by cooperation between loggers and planters or by securing volume of business through the coordination of local forest management.

To compare the effects of these improvements on optimal cutting age, and because there countless sets of conditions for simultaneous harvesting may exist, several potential parameters for improvement of each operation were assumed (Table 2).

Planting and Silvicultural Costs and Subsidies

The man-days of work and other costs required for silvicultural operations without subsidy are shown in Table 3. These were provided in an interview of the Forest Owners' Association at Kaneyama Town, Yamagata Prefecture. Current subsidy rates for silvicultural operations are intricately established according to stand classification under forest zon-

Table 1 Examples of harvesting parameters of a 1-ha stand under four thinning systems

		Stand age						
No commercial thinning	unit	50	55	60	65	70	75	80
Mean volume per tree	m^3	0.48	0.58	0.68	0.79	0.88	0.98	1.07
Total volume of standing trees	m^3	460	544	626	711	781	850	914
Gross income of clear-cutting	yen	4,445,000	5,339,000	6,213,000	7,025,000	7,817,000	8,491,000	9,083,000
One commercial thinning at stands of 50 years								
Mean volume per tree	m^3	(0.50)	0.59	0.71	0.82	0.94	1.05	1.17
Total volume of standing trees	m^3	(124)	434	508	585	659	729	799
Gross income of clear-cutting	yen	(1,104,000)	4,170,000	5,084,000	5,911,000	6,776,000	7,555,000	8,363,000
Two commercial thinnings at stands of 50 and 70 years								
Mean volume per tree	m^3	(0.50)				(0.98)	1.09	1.23
Total volume of standing trees	m^3	(124)				(174)	576	644
Gross income of clear-cutting	yen	(1,104,000)				(1,699,000)	5,915,000	6,715,000
Three commercial thinnings at stands of 50, 70 and 90 years								
Mean volume per tree	m^3	(0.50)				(0.98)		
Total volume of standing trees	m^3	(124)				(174)		
Gross income of clear-cutting	yen	(1,104,000)				(1,699,000)		

		Stand age					
No commercial thinning	unit	85	90	95	100	105	110
Mean volume per tree	m^3	1.16	1.24	1.33	1.40	1.47	1.53
Total volume of standing trees	m^3	977	1027	1080	1126	1167	1213
Gross income of clear-cutting	yen	9,572,000	10,023,000	10,481,000	10,848,000	11,206,000	11,421,000
One commercial thinning at stands of 50 years							
Mean volume per tree	m^3	1.27	1.38	1.49	1.59	1.68	1.77
Total volume of standing trees	m^3	861	925	985	1043	1091	1144
Gross income of clear-cutting	yen	9,047,000	9,663,000	10,423,000	11,020,000	11,561,000	12,194,000
Two commercial thinnings at stands of 50 and 70 years							
Mean volume per tree	m^3	1.36	1.49	1.63	1.76	1.86	1.98
Total volume of standing trees	m^3	709	771	838	900	947	1008
Gross income of clear-cutting	yen	7,597,000	8,440,000	9,248,000	10,084,000	10,787,000	11,562,000
Three commercial thinnings at stands of 50, 70 and 90 years							
Mean volume per tree	m^3		(1.55)	1.69	1.84	2.00	2.16
Total volume of standing trees	m^3		(202)	659	715	772	832
Gross income of clear-cutting	yen		(2064000)	7,159,000	8,079,000	8,964,000	9,902,000

Note: values in parentheses represent commercial thinning; all other values represent clear-cutting.

Table 2 Assumed extents of improvements per stand achieved by simultaneous harvesting

	Assumed amount	Unit
Shortening the length of newly-constructed yarding roads	0, 50, 100*, 200	m
Reducing the frequency of machine transportation	1**	time
Reducing site preparation cost	Half the standard***	
Increasing annual operation rate of forestry machines	50, 75*, 100	****

* Standard assumption.
** One-way transportation is assumed to be omitted.
*** According to an interview of the Forest Owners' Association at Kaneyama Town, Yamagata Prefecture.
**** Annual operation rate with simultaneous harvesting is set to the standard rate of 100 (National Forestry Extension Association in Japan, 2001).

Table 3 Man-days of work and costs incurred for silvicultural operations per ha

	Operated stand age (year)	Man-days of work	Wage per one operation (yen)	Additional costs (yen)
Site preparation	1	30	332,100	
Planting	1	20	221,400	200,000
Weeding	1 to 8	10	110,700	
Cleaning	13	15	166,050	
Precommercial thinning	20 and 30	15	166,050	

Table 4 Main fixed parameters of stands and logging

Stand area	1 ha
Mean hauling distance by forwarder	200 m
Mean stand incline	20 degrees
Mean prehauling distance	30 m
Shortest distance from forest road to stand	150 m
Wage for silvicultural operations	11,070 yen/day
Wage for machine operator	20,000 yen/day
Wage for chainsaw operator	17,500 yen/day
Truck fee for transporting a set of machines	41,784 yen
Yarding road construction cost	1,500 yen/m

ing etc., and systems vary by municipality. I assumed the following subsidy rates, which were applied to all silvicultural operations, from site preparation to precommercial thinning: 0%, 50%, 70% (standard assumption), 85%, and 100%. Assumptions of high subsidy rates can be also understood as assumptions by which it is possible to conduct silvicultural operations more efficiently than can be done currently without degrading the forest.

Ground Rent and Management Cost

Annual ground rent and management costs were considered together because they can collectively be referred to annual costs as long as they are assumed to be constant. Thus, they are hereafter referred to as 'annual cost' and assumed to be 0, 5,000, 10,000 (standard assumption), 15,000, and 20,000 yen/ha.

Assumed Standard Parameters of Stands and Logging

The main fixed parameters of stands and logging assumed as standards are shown in Table 4. The assumed stand area, i.e. thinning and clear-cutting area in single harvesting, is 1ha and seems to be small for efficient forest management operations, but in many Japanese regions average stand size is even smaller, and it is a proper assumption in order to observe the effect of simultaneous harvesting.

Discount Rate

I used discount rates of every 0.5% between 0.5% and 4%. Note that, by definition, a rate of 0% for SEV and PVFP is not applicable. Preliminary calculations indicated that 4% was too high to obtain a positive net financial yield under the assumed parameters.

Current Stand Age

Current stand age is a necessary parameter to calculate PVFP. Although current stand ages were defined in 10-year increments from 0 to 50, 40 years was adopted as the standard stand age because it is the typical age for the initiation of commercial thinning in Japanese conifer plantations.

Calculations

The economic yield (gross incomes minus logging costs) from commercial thinning and clear-cutting was calculated for each of 13 cutting rotations from 50 to 110 years at intervals of 5 years with interest charged. Then, for each combination of stand and simultaneous harvesting condition parameters, I summed up the economic yield from commercial thinning and clear-cutting as a present value at the time of clear-cutting and fitted to it a regression curve. This was used to calculate SEV, PVFP and FR for single harvesting (harvesting only the stand of concern) and simultaneous harvesting (harvesting the stand of concern and the adjacent stand together), and using them, I determined the optimal cutting ages, acceptable ranges, and their changes under simultaneous harvesting.

Although the acceptable times of commercial thinning changed intermittently as cutting age increased, the preliminary calculations indicated that the cubic curves fit well with the sum of economic yields. For example, when standard parameters were applied, both decision coefficients for the sums of economic yields with single harvesting and simultaneous harvesting were greater than 0.999. Xu and the differentials for SEV, PVFP, and FR are expressed as:

$$Xu = a_1u^3 + a_2u^2 + a_3u + a_4 \tag{4}$$

$$\frac{dNPV}{du} = \frac{3a_1u^2 + 2a_2u + a_3 - Co(1+p)^u \log(1+p)}{(1+p)^u - 1} - \frac{(a_1u^3 + a_2u^2 + a_3u + a_4 - Co(1+p)^u)(1+p)^u \log(1+p)}{((1+p)^u - 1)^2} \tag{5}$$

$$\frac{dPVFP}{du} = \frac{1}{(1+p)^{u-u0}}\left(\frac{-(b+v)\log(1+p)}{p} - (a_1u^3 + a_2u^2 + a_3u + a_4 + NPVmax)\log(1+p) + 3a_1u^2 + 2a_2u + a_3\right) \tag{6}$$

$$\frac{dFR}{du}=2a_1u+a_2-\frac{(a_4-Co)}{u^2}\ , \tag{7}$$

where a_1, a_2, a_3, and a_4 are constants.

As shown in Equations (5), (6), and (7) (although it is not obvious in Equation (6)), by definition, annual cost has no effect on differentials or optimal cutting ages For PVFP, $u0$ is also irrelevant to the sign of the differentials and optimal cutting ages, as shown by JOHANSON and LÖFGREN (1985).

All calculations were done using Microsoft Excel 2007 and Visual Basic for Applications (VBA). Although specifying cutting age too finely (e.g., 75.22 years) has little meaning in real forestry, optimal cutting ages were estimated to the hundredth of a year and acceptable ranges to half a year. However, these values should be properly rounded for interpretation.

To observe the effect of each parameter on optimal cutting age, individual parameter values were changed by rotation while others were left constant, and the resulting outputs were observed.

RESULTS AND DISCUSSION

Results under All Combinations of Parameters

FR

Optimal cutting ages for FR were 110 years under all combinations of parameters, including with highest discount rate of 4%. The upper edges of the acceptable range were also 110 years, and no shift of optimal cutting age was apparent with simultaneous harvesting. The lower edges of the 95% and 1,000 yen/ha ranges were over 104 years with single harvesting and 102 years with simultaneous harvesting. Because the differences among results with varying parameter values were negligible, further explanations for FR are omitted hereafter.

Optimal cutting age and acceptable range

Optimal cutting ages with simultaneous harvesting under all combinations of parameters were within the acceptable ranges for a single harvesting for SEV, PVFP, and FR. This means that shifts in optimal cutting ages were small compared to the range of acceptable cutting age, irrespective of stand and simultaneous harvesting conditions.

Characteristics of PVFP

In all cases, the optimal cutting ages of SEV and PVFP were almost identical, and the differences between the two were always less than 1 year. In addition, current stand age had no effect on the optimal cutting ages of PVFP, as explained above. However, the acceptable ranges could differ considerably.

Outputs under the Standard Combination of Parameters

The calculated logging costs and cost reductions by simultaneous clear-cutting are shown in Table 5 to illustrate the efficiency of the assumed logging system. As shown, the effi-

Table 5 Examples of logging costs and cost reductions by simultaneous clear-cutting (yen/m^3) with standard parameters and 3% discount rate

	Stand age												
	50	55	60	65	70	75	80	85	90	95	100	105	110
①Total logging cost in single harvesting	8,706	8,039	7,561	7,170	6,924	6,723	6,085	5,958	5,842	5,753	5,731	5,662	5,603
Yarding road construction	1,304	1,103	958	844	768	706	280**	254	233	215	252	233	216
Machine transportation	260	219	191	168	153	140	185	168	155	142	167	155	143
Fixed and variable costs	3,857	3,529	3,293	3,110	2,987	2,887	2,700	2,630	2,575	2,526	2,467	2,433	2,406
Others*	1,926	1,830	1,761	1,690	1,658	1,631	1,562	1,547	1,520	1,511	1,486	1,483	1,480
Truck fee	1,358	1,358	1,358	1,358	1,358	1,358	1,358	1,358	1,358	1,358	1,358	1,358	1,358
②Total cost-cuttings by simultaneous harvesting	1,214	1,053	459	396	349	387	345	311	285	327	301	278	257
Machine transportation	130	110	118	102	91	104	93	84	77	91	83	77	72
Yarding road construction	559	473	152**	132	117	134	120	109	100	117	108	100	93
Site preparation	150	127	136	118	105	120	107	97	90	105	97	89	83
Fixed costs affected by operation rate of machines	375	344	54	44	36	30	25	21	18	15	13	11	9
Adopted thinning system (times of commercial thinning) with:													
single harvesting	0	0	0	0	0	0	2	2	2	2	3	3	3
simultaneous harvesting	0	0	1	1	1	2	2	2	2	3	3	3	3

* Others include stockyard cost, human transportation cost and collateral labor cost.
** The amount of yarding road construction or its cost reduction decreases at this stand age because, after this cutting age, commercial thinning was adopted and a portion of road was assumed to be constructed during commercial thinning.
Note: The total logging cost of simultaneous harvesting is calculated by ① − ②.

ciency of the assumed logging system is not originally high, even for simultaneous harvesting. This is one reason SEV is often negative under many combinations of parameters.

The outputs under the standard combination of parameters are shown in Table 6 and Fig. 2. It is generally accepted that optimal cutting age is strongly affected by discount rate and optimal cutting ages for SEV with ordinary discount rates are much younger than those for FR in order to pay back the debts of planting and silvicultural costs with interest charged. Based on the assumption of standard parameters with discount rates of less than 2.5%, optimal cutting ages did not appear below 110 years. This means that the actual optimal cutting age, without a limitation of 110 years, should be 110 years or older. Thus, the actual acceptable ranges should also be older. In addition, the actual acceptable ranges should be wider than the calculated range of 50–110 years when data are not limited.

These results highlight the fact that all definitions of acceptable ranges have drawbacks. The 50,000 and 100,000 ranges are subjective, and the relative size compared to optimal financial yield is not stable. In contrast, the 5% and 10% ranges are objective, but they are not applicable to cases for which the optimal financial yield is negative, nor are they suitable when the optimal financial yield is positive but very small. The acceptable range should be defined based on personal preference of the forest owner; however, for the purposes of this

Table 6 Optimal cutting age, optimal financial yield, and range of acceptable cutting age calculated using the standard combination of parameters

Discount rate		(Unit)	SEV single harvesting	SEV simultaneous harvesting	PVFP ** single harvesting	PVFP ** simultaneous harvesting
	Optimal cutting age	(yr)	110	110	110	110
	Money yield	(yen)	2,861,081	3,436,361	5,637,127	6,496,675
	Acceptable range*	(yr)				
1%	50,000yen		108.5 − 110	108 − 110	108.5 − 110	108 − 110
	100,000yen		106.5 − 110	105.5 − 110	106.5 − 110	105.5 − 110
	5%		105 − 110	102.5 − 110	98.5 − 110	94.5 − 110
	10%		99 − 110	95 − 110	83 − 110	79 − 110
	Optimal cutting age	(yr)	110	110	110	110
	Money yield	(yen)	201,366	412,534	2,293,954	2,760,767
	Acceptable range*	(yr)				
2%	50,000yen		88.5 − 110	84 − 110	100 − 110	91.5 − 110
	100,000yen		74 − 110	74.5 − 110	86.5 − 110	82 − 110
	5%		106.5 − 110	95 − 110	83 − 110	77.5 − 110
	10%		102.5 − 110	86.5 − 110	68.5 − 110	67.5 − 110
	Optimal cutting age	(yr)	70.83	74.62	70.75	74.66
	Money yield	(yen)	−367,554	−264,360	1,301,035	1,634,719
	Acceptable range*	(yr)				
3%	50,000yen		57.5 − 110	59.5 − 110	61.5 − 86.5	64.5 − 91.5
	100,000yen		53.5 − 110	55 − 110	58.5 − 98.5	61 − 102
	5%		N/A***	N/A***	60.5 − 90	62 − 98
	10%		N/A***	N/A***	57.5 − 107.5	58.5 − 110
	Optimal cutting age	(yr)	62.43	64.17	62.4	64.18
	Money yield	(yen)	−510,658	−458,373	943,289	1,192,740
	Acceptable range*	(yr)				
4%	50,000yen		51 − 95	52.5 − 98.5	56 − 71.5	57.5 − 74
	100,000yen		50 − 110	50 − 110	54 − 77.5	55.5 − 80.5
	5%		N/A***	N/A***	56.5 − 71	57 − 75.5
	10%		N/A***	N/A***	54 − 76.5	54.5 − 82.5

* When the calculated optimal cutting age is 110 years, the actual optimal cutting age should be equal to or older than 110 years and then the actual acceptable range should be also older.
** Current stand age was assumed to be 40 years.
*** 5% and 10% range could not be calculated because NPV was negative.

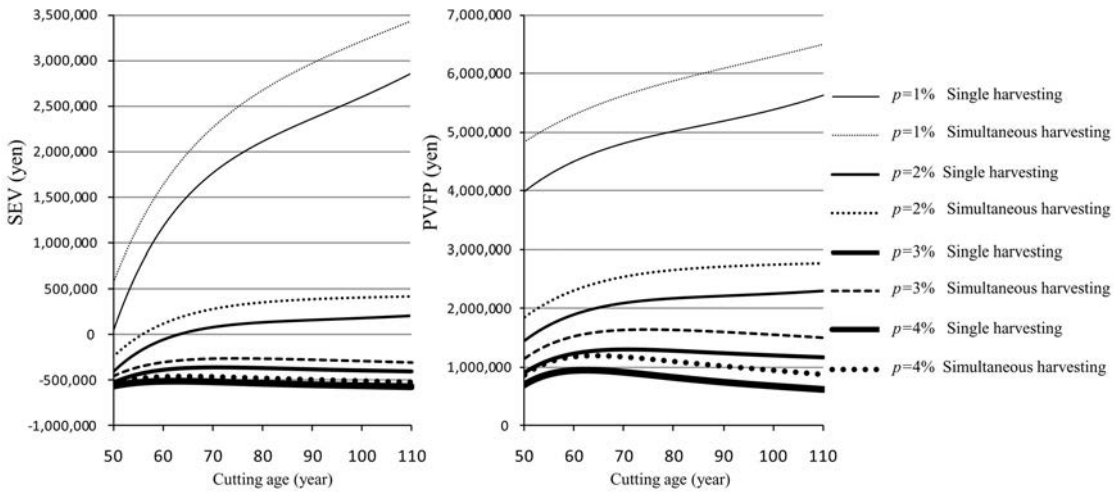

Fig. 2 Relationships among cutting age, discount rate, and SEV or PVFP

research, I assumed that the cutting age is acceptable, though not optimal, if it is within 50,000 or 95% range.

The results of money yield in Table 6 show that the discount rate which allows to make SEV positive under the standard combination of parameters is less than 2.5%. Because currently interest rates are very low in Japan under Japanese government's ultra-low interest rate policy (e.g. the average interest rate of 10-year Japanese government bond during 2009 is 1.358% (Ministry of Finance Japan, 2010)) and interest rates of typical loan for forestry from Japan Finance Corporation are around 1.60–1.75% (Japan Finance Corporation, 2010), there are some possibilities for forest owners possessing bare land with condition the same as the standard assumption to decide to start timber production forestry, but the estimated level of profitability is generally too low to believe forestry here as economically promising, compared to other investments.

On the other hand, values of PVFP in Table 6 are positive, meaning that this standard stand is valuable. However, when the assumed discount rate is large and SEV is negative, the money yield from second rotation is negative and economically the most reasonable way of managing this stand can be to harvest it and leave it without replantation.

Effect of Change on Each Parameter

Planting and Silvicultural Costs and Subsidies (Fig. 3)

The optimal cutting ages and acceptable ranges increased as the subsidy rates for planting and silvicultural operations decreased and as discount rate increased. In all cases, shifts in optimal cutting ages were small compared to acceptable ranges, and the optimal cutting ages with simultaneous harvesting were within the acceptable range for a single harvesting. Increasing regeneration costs leads to shorter optimal cutting age in general, but in this simulation, estimated money yield was negative with lower or none subsidy rate and then the optimal cutting age were longer rather than shorter in order to make deficit smaller.

The result suggests that the policies for subsidizing a forest owner's planting and silvicultural operations must have shortened optimal cutting ages and acceptable ranges. However, it is not clear whether increasing the subsidy rate from 70% to 100% has a further effect on the optimal cutting ages.

PVFP and current stand age

As explained above, current stand age had no effect on optimal cutting ages for PVFP, but the acceptable ranges narrowed as the current stand ages increased (Fig. 4). This suggests that PVFP is sensitive to cutting age when the current stand age is high. Although narrow acceptable ranges were only seen with high discount rates, even for PVFP, attention should be paid to any possibility of narrowing the acceptable range, given that no case occurred where PVFP was negative because past costs were neglected.

Maximum and minimum effects of simultaneous harvesting

Among all combinations of parameters, the effect of integration was maximized in cases for which the operation rate of machines with a single harvesting was assumed to be 50%, and the reduction in the length of yarding roads to be constructed was 200 m. Conversely, when the former was 100% and the latter was 0 m, the effect was minimized. The effects of simultaneous harvesting on optimal cutting ages were small, except when the discount rate was 2.5%, which resulted in a reduction in the optimal cutting age under simultaneous harvesting (Fig. 5). Even in that case, the shift only brought about a slight difference in SEV and PVFP, and the new optimal cutting age was within the acceptable range for a single harvesting. These results illustrate that the effects of simultane-

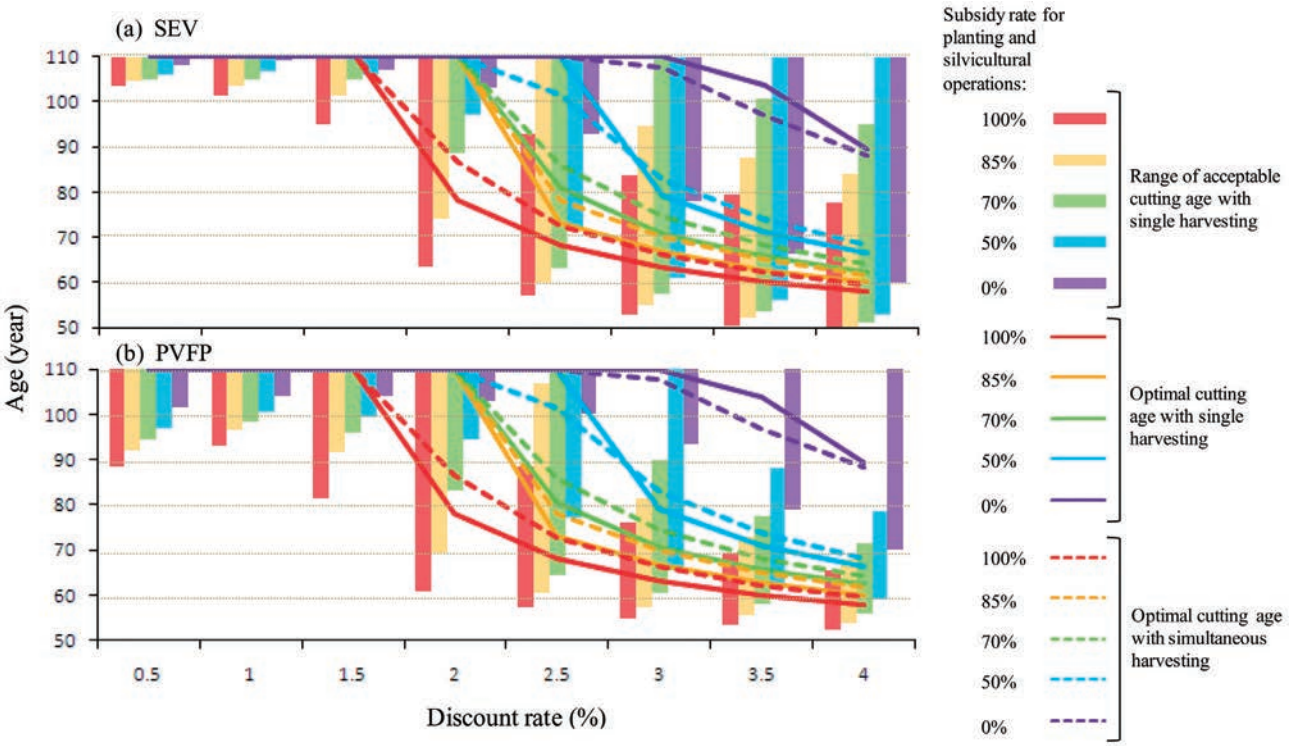

Fig. 3 Relationships among optimal cutting age, range of acceptable cutting age, discount rate, and subsidy rate for planting and silvicultural operations

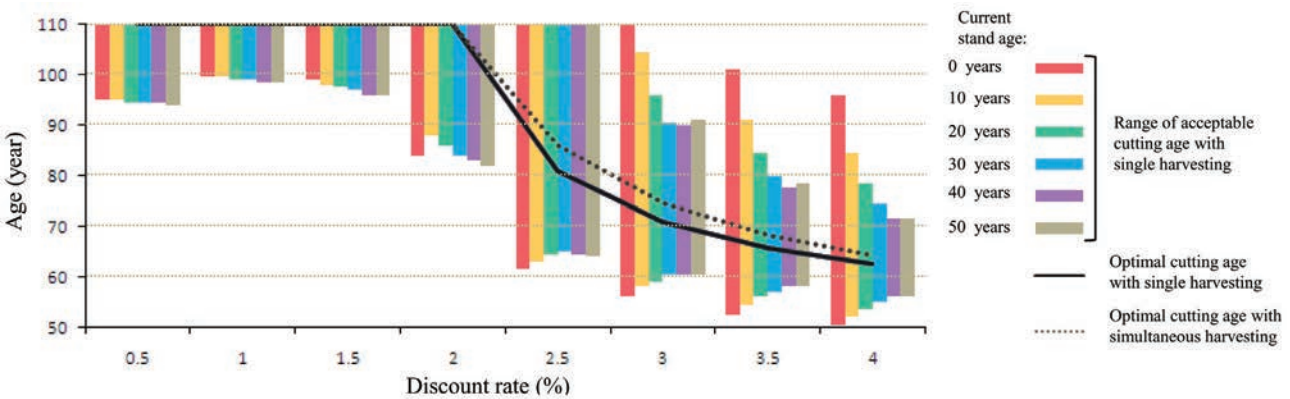

Fig. 4 Relationships between optimal cutting age and range of acceptable cutting age according to PVFP, discount rate, and current stand age

Note: Optimal cutting age is the same regardless of the current stand ages.

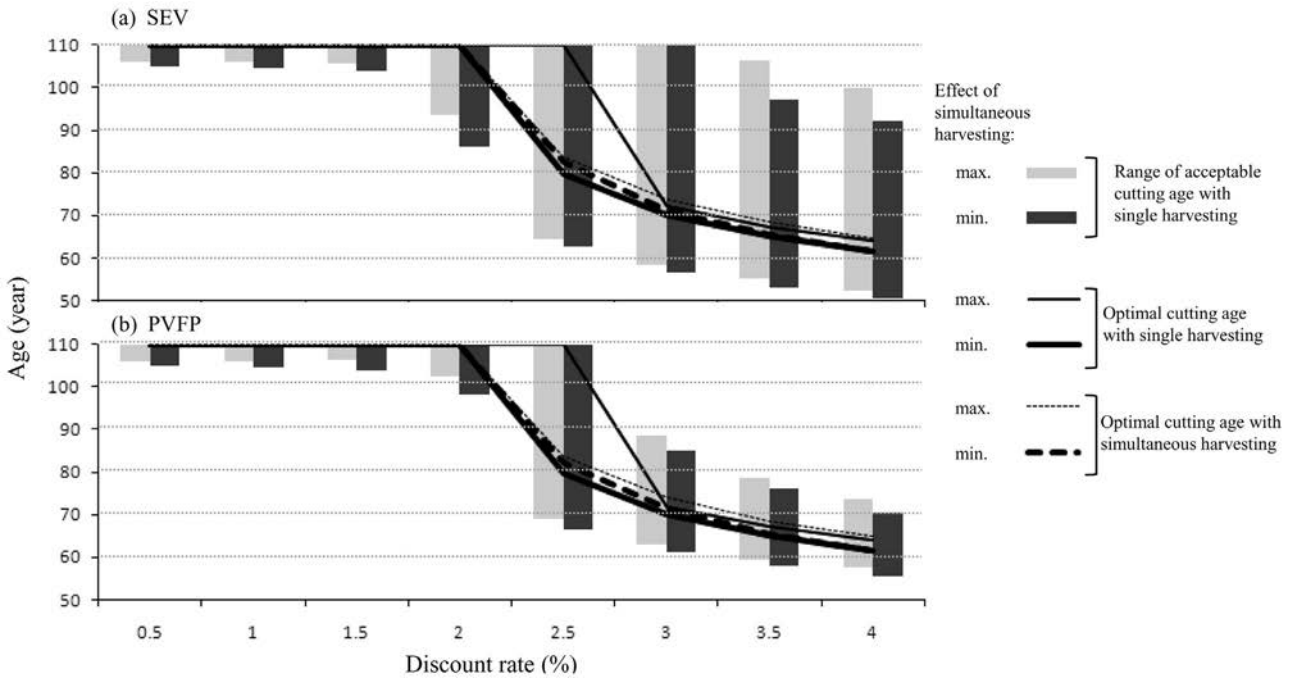

Fig. 5 The maximum and minimum effects of simultaneous harvesting on optimal cutting age and range of acceptable cutting age

ous harvesting on the optimal cutting age were much smaller than were the effects of discount rate, and than the width of acceptable range.

CONCLUSION

Although this research simulated SEV, PVFP, and FR under only one logging system, the results imply that the shifts of optimal cutting ages by integration are small compared to the range of acceptable near-best cutting ages, and the widths of the acceptable ranges are quite broad (except when the optimal cutting ages are too old to make calculation of acceptable ranges possible). Therefore, forest managers can decide the spatial and temporal distribution of harvesting stands to achieve economic and social benefits of forests without being concerned about the dispersal of current stand ages and the optimal cutting ages of adjacent stands. They can then make decisions whether to harvest stands or not without referring to the optimal cutting age and acceptable range for simultaneous harvesting, but rather by referring to those calculated based on a single harvesting, which are more easily estimated. If forest managers or owners focus on PVFP, thereby ignoring past costs, it is more important to adopt a near-optimal cutting age than when focusing on SEV and FR.

It is important to assume that a stand exhibits the characteristics that enable it to be harvested alone because this allows comparisons of the results obtained with single harvesting and those obtained with simultaneous harvesting. For example, for this study, stand areas were fixed at 1 ha, which is the appropriate size for observing the effects of simultaneous harvesting on acceptable cutting age. This is because single harvesting is difficult in very small stands, and the effects of simultaneous harvesting are relatively reduced in larger stands, given that cost reduction by simultaneous harvesting is mainly classified as a fixed cost. The assumption that simultaneous commercial thinning is always possible should be modified considering that the current ages of adjacent stands might differ considerably.

ACKNOWLEDGMENT

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Article

Extraction of Production Forests for Sustainable Forest Management Based on Economic Balances in Kanuma Area of Tochigi Prefecture

Ayami Murakami*, Kaname Ito*, Masashi Saito*,
Kazuhiro Aruga* and Toshiaki Tasaka*

ABSTRACT

This study developed the method to extract production forests based on economic balances with considering regeneration expenses for sustainable forest management. This study defined production forests as forests where expected revenues at clear cutting surpassed all costs such as harvesting and regeneration expenses. These revenues and costs were estimated based on forest registration and GIS data. The study site was Kanuma Area of Tochigi Prefecture. From the results of the double log prices their level from 1981, this model could relatively accurately estimate a variety of revenues and costs according to log prices. According to the result on the current conditions with considering regeneration costs, only 1.93% was extracted as production forest candidates. Thus, the implication is that conducting sustainable forest management at cutting age, 60 years is difficult based on the current conditions in this area other than 1.93% stands. This could be the reason why 94% of the forests are classified as those intended for water and soil conservation although Kanuma area is one of the famous forestry areas in Tochigi Prefecture. This situation occurred due to low log prices and high costs. All costs on smaller areas, subsequently volumes of subcompartments were much more expensive than log prices of even Hinoki cypress because all costs included indirect costs which were almost all fixed costs, the smaller the areas, subsequently the volumes, the higher the costs. Therefore, it will be necessary to decrease all costs considerably by extending forestry-operation sites while merging small subcompartments. Moreover, estimations that involved cutting ages set at 80, 100, and 120 years were conducted while considering long-term rotation management. However, the percentage of production-forest candidates increased a little because there was no change in the quality of logs, subsequently log prices. This study did not consider effects of changing log prices along with log quality and some kinds of subsidies. Developing the forest-road networks and extending forestry-operation sites through the merger of small subcompartments should be also examined. The next study will analyze these effects and which factors have the ability to decrease costs.

Keywords: production forests, economic balances, forest zoning, Kanuma area, sustainable forest management

INTRODUCTION

Forest zoning was introduced in Japan when the Forest and Forestry Basic Act was revised in 2001. All forests were classified into three types under the zoning plan: (1) forests for water and soil conservation, (2) symbiotic forests with people, and (3) forests for resource cyclic use. The emphasis in forests for water and soil conservation involves nurturing river sources and preventing disasters in mountainous regions. In symbiotic forests with people, the goals are to maintain forest ecosystems, preserve living environments, and consider appropriate utilization of forest spaces. Forests for resource cyclic use are reserved for the cultivation of wood and other forest products.

Furuido (2001), Oka (2001), and Kohroki (2003) have noted close relationship between forest zoning and forest function valuation, and importance of establishment on the method of valuation for forest functions. Forest function valuation has been considering forest public functions such as watershed protection, health culture, mountainous district disaster prevention, and timber production. However, it has not been considering whether sustainable forest management can be conducted or not. Therefore, this study developed the method to

Corresponding author: Ayami Murakami
E-mail: ayamy_mumu@yahoo.co.jp
* Utsunomiya University, 350 Mine, Utsunomiya 321-8505, Japan

extract production forests for sustainable forest management, mainly economical maintenance and sustained yield, based on economic balances in order to conduct valuation for one of the forest functions, timber production with considering sustainable forest management.

Some prefectures have established their own forest-zoning divisions in addition to those introduced based on the national laws (TSUJIUCHI, 2005). In Mie Prefecture, for example, forests were divided into two definitions such as environment forests and production forests. However, production forests were divided based on two simple definitions such as the planted forests within 400 m from roads and the planted forests with conducting forest management even beyond 400 m other than environmental forests. Thus, the definitions have not considered economic balances. IWAOAKA (2005) analyzed economic balances at clear cutting. However, the study has not considered regeneration expenses which are important to conduct sustainable forest management.

Therefore, this study developed the method to extract production forests based on economic balances with considering regeneration expenses for sustainable forest management. This study defined production forests as forests where expected revenues at clear cutting surpassed all costs such as harvesting and regeneration expenses. These revenues and costs were estimated based on forest registration and GIS data.

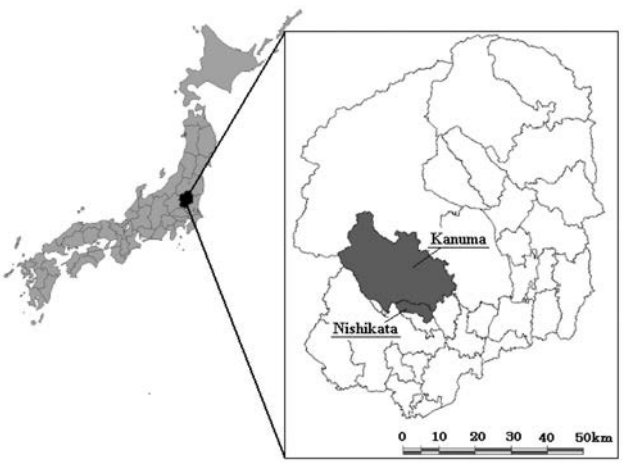


Fig. 1 The study site

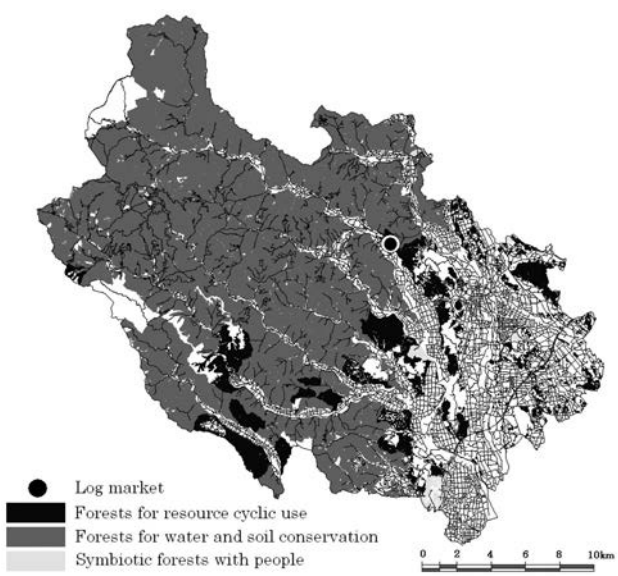


Fig. 2 Forest zoning in the study site

STUDY SITE AND MATERIAL

The study site was Kanuma area, consisting of Kanuma city and Nishikata town (Fig. 1). This area is located in the upper area of the Watarase River Watershed. This area encompasses 52,000 hectares, of which about 65% is covered by forests. Most of the tree species are conifers; Japanese cedar and Hinoki cypress account for 54% and 23% of the trees, respectively. Most of conifers are within 45-50 years old. Kanuma area is one of the famous forestry areas in Tochigi Prefecture. However, Kensei Forest Management Office of Tochigi Prefectural Government has allowed local forest owners to extend cutting ages because of forest-management conditions during periods of decreasing log prices, and for reasons of water and soil conservation (ONISHI, 2007). Therefore, 94% of the forests are classified as those intended for water and soil conservation instead of forests for resource cyclic use (Fig. 2). According to site-index which indicates the order of the production capacity of the stands by three classes and the smaller number is, the larger production capacity is. Site-index 1 is 53%, Site-index 2 is 43%, and Site-index 3 is 4%. As for the operation-site inclination, most of forests are relatively steep, 30 degrees or more. The density of the road network in the Kanuma area is relatively high, 44.83 m/hectare.

Forest-registration data (stand ages, tree species, and site indexes) and GIS data (information on roads and subcompartment layers) from the Tochigi Prefectural Government were used in the study, as were 50 m-grid digital elevation models (DEM) from the Geographical Survey Institute. Data were converted into 50 m-grid raster data for consistency with DEM data. In order to estimate expected revenues at clear cutting, all costs such as harvesting and regeneration expenses and to extract production forests which were defined as forests where revenues surpassed all costs, a program was created using Microsoft Visual C++.

METHOD

Estimation of Revenue

In this study, the cutting ages were set to 60 years. The volume for each subcompartment was estimated using yield

Table 1 Yield table

Age	Volume (m^3/hectare)					
	Cedar	Cypress	Cedar	Cypress	Cedar	Cypress
	Site Index 1		Site Index 2		Site Index 3	
10	54.5	40.2	34.0	30.3	20.5	23.2
15	149.9	92.3	99.6	64.6	61.3	44.2
20	244.9	140.4	169.6	101.4	109.5	67.4
25	329.5	184.8	234.4	135.6	155.2	92.5
30	403.5	225.1	291.2	166.8	197.2	116.7
35	471.5	260.0	344.3	194.6	236.2	138.8
40	534.5	290.7	394.0	219.4	272.6	158.6
45	593.6	318.3	439.5	241.4	306.8	175.8
50	649.8	342.7	483.0	261.1	339.0	190.2
55	702.1	364.8	523.6	278.4	369.3	201.8
60	751.3	384.4	561.6	294.0	397.9	210.0
65	797.5		597.2		424.9	
70	841.0		630.5		450.5	
75	881.9		662.0		474.9	
80	920.8		691.8		498.2	
85	958.0		720.8		520.6	
90	993.4		748.8		542.2	
95	1027.3		776.0		563.2	
100	1059.9		802.5		583.6	

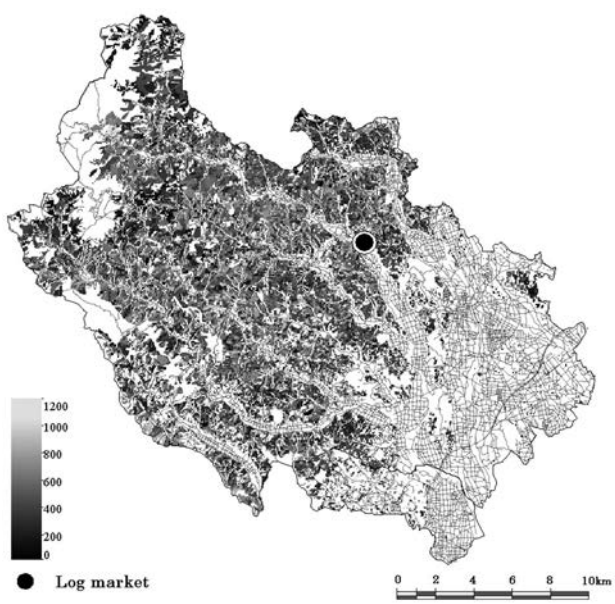


Fig. 3 Current volumes (m^3/hectare)

tables (Table 1, Forestry examination plantation of The Forestry Agency 1955 and 1962) with stand species, ages, and site indexes in the present forest registration. Fig. 3 shows volumes in current situations. We set out to study only Japanese cedar and Hinoki cypress, which are major species in Japanese plantation forests. There are a few subcompartments having over 1,000 m^3/hectare because of some old growth forests.

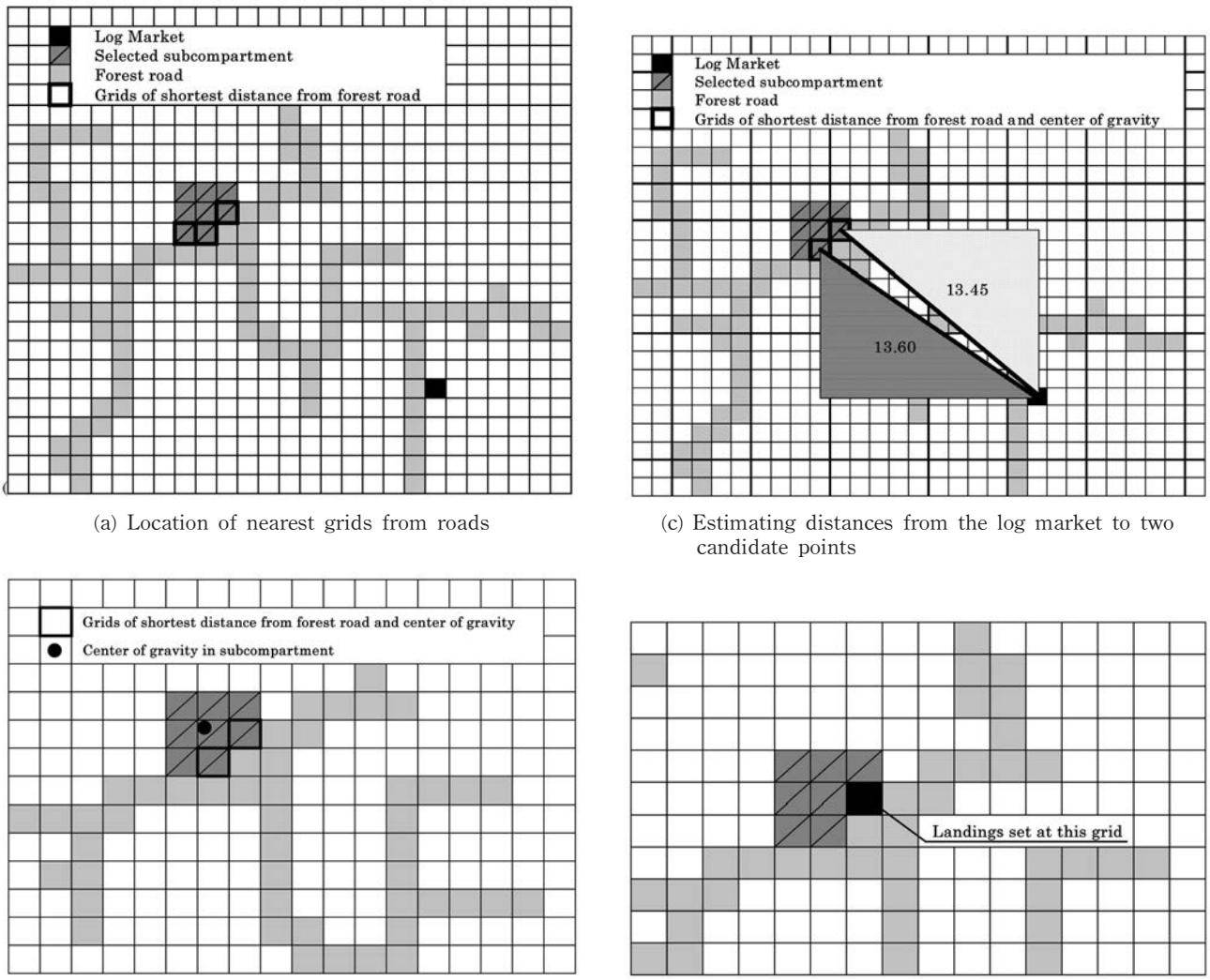
Then, revenues were estimated using the amount of harvest volumes at the cutting ages and log prices: 13,187 yen/m^3 for Japanese cedar and 21,533 yen/m^3 for Hinoki cypress, according to 2008 Forestry Cooperatives Association prices in Tochigi Prefecture (as of Sept. 9, 2009, USD1 was equivalent to 92.45 yen). However, this study did not consider revenues from thinned woods.

Logging Distance

Logging distances, which meant skidding, forwarding, and yarding distances in this study, were estimated as average distances from landings to all grids within subcompartments. Landings were set within grids in such a manner as to minimize distances from roads, centers of gravity in subcompartments, and log markets (Fig. 4). Logging distances are shown in Fig. 5. The log market managed by Kanuma Forestry Cooperative was selected in the analysis.

Transportation Distance

For simplicity, transportation distance was estimated using a straight-line distance from a landing in each subcompartment to the log market, taking into account the detour ra-



(a) Location of nearest grids from roads

(c) Estimating distances from the log market to two candidate points

(b) Location of nearest grids from center of gravity

(d) Decision of a landing

Fig. 4 Method to set up landings

tio (Fig. 6), which was reference from the physiographic division (KOBAYASHI, 1997). The terrain of the study site is relatively steep; therefore, the detour ratio was set to 0.4.

Harvesting-Operation System

In this study, we assume that the felling, processing (delimbing and bucking), piling, and transporting of trees were conducted by chainsaw, processor, grapple-loader, and 8-ton truck, respectively. Logging machines (Fig. 7) were categorized into five types–tractor, forwarder, small and medium tower-yarder, and yarder (ARUGA *et al.*, 2006)–with the type used based on logging distances (Fig. 5), inclinations of operation sites, and logging directions. Inclinations of operation sites were estimated using logging distances and differences in elevation values from landings to all grids in subcompartments. Logging direction were estimated using differences in elevation values from landings to all grids in subcompartments. For example, when elevation values of landings were higher than average elevation values of all grids in subcompartments, logging directions were uphill. Selected machines are shown in Fig. 8. Operating systems were classified into five types based on logging machines (Fig. 9). In this study, we assumed that tractors, small and medium tower-yarders, and yarders were used in whole-tree logging, and that forwarders were used in cut-to-length (CTL) processes. Since CTL involved processing before logging, we assumed that processing was conducted by chainsaw in the forests instead of by processor on the landings.

Estimation of All Costs

After operating systems were selected, productivity and all

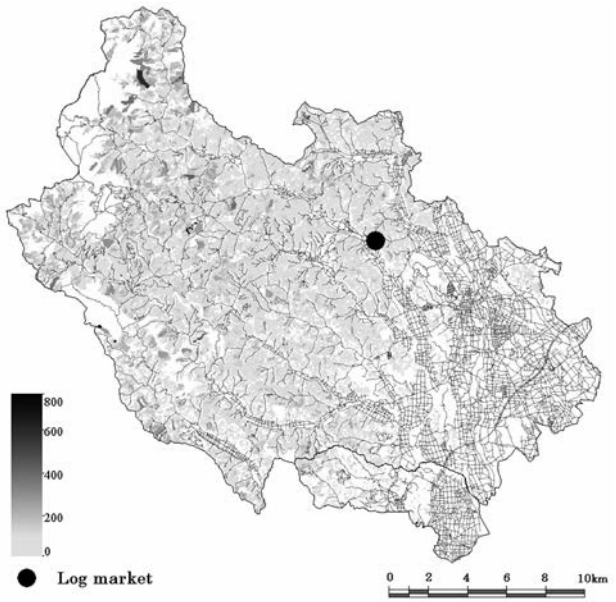


Fig. 5 Logging distances (m)

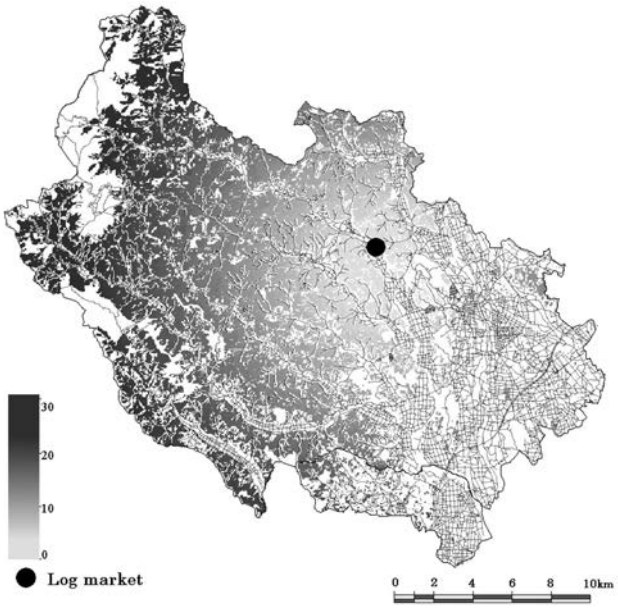


Fig. 6 Transportation distances (km)

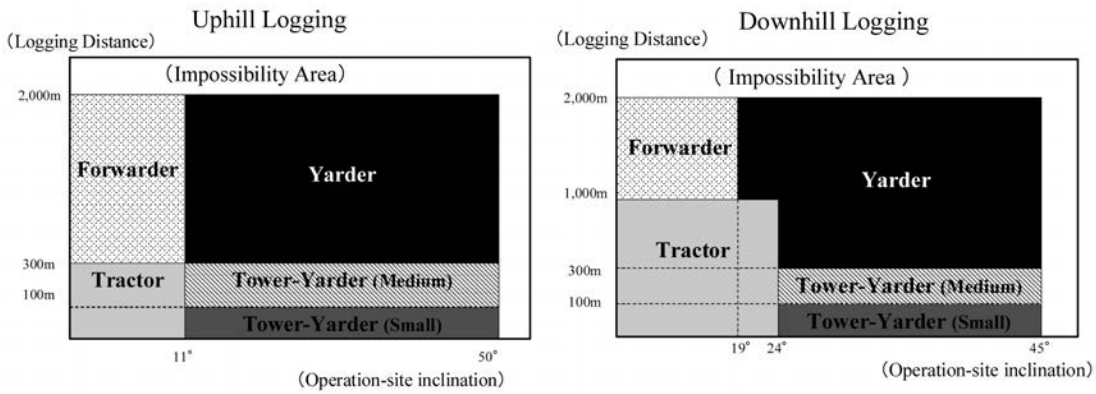


Fig. 7 Logging machine selection

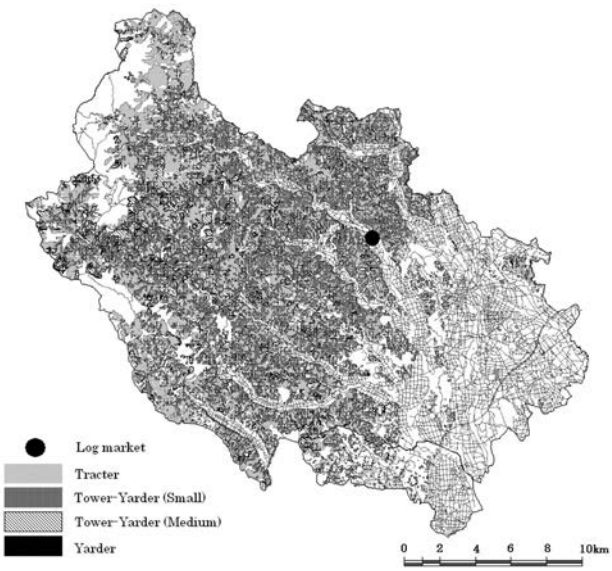
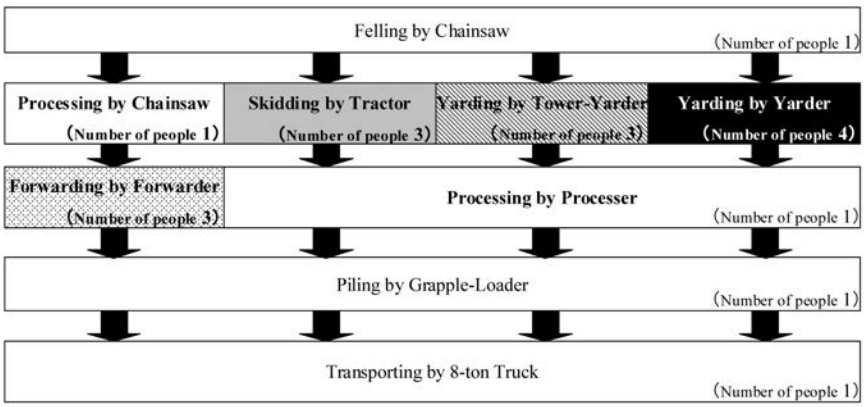


Fig. 8 Selected logging machines



	Forwarding by Forwarder	Skidding by Tractor	Yarding by Tower-Yarder	Yarding by Yarder
Number of machines	3	4	4	4

*excluding chainsaw

Fig. 9 Harvesting-operation systems

Table 2 Operational expenses of selected machines

Machine	Operation	Expenses (yen/m^3)
Chainsaw	Felling	699
Chainsaw	Processing	280
Processer	Processing	1,774
Tractor	Skidding	$1.031Ly+27{,}510e^{0.117\theta}/V+1{,}669$
Forwarder	Forwarding	$0.459Ly+13{,}500e^{0.117\theta}/V+1{,}943$
Tower-Yarder (Small)	Yarding	$14.925Ly+1{,}262{,}250/LyV+617$
Tower-Yarder (Medium)	Yarding	$8.369Ly+1{,}893{,}375/LyV+1{,}143$
Yarder	Yarding	$759.532Ly^{0.2142}+1{,}635{,}876/LyV+104{,}009/V+196$
Grapple-Loader	Piling	303
8-Ton Truck	Transporting	$0.026Lt+778$

*1. Ly denotes Logging Distance (m), *2. V denotes Harvesting Volume (m^3/hectare), *3. θ denotes Operation Place Inclination (°), *4. Lt denotes Transportation Distance (m).
Cited from SAWAGUCHI (1996) and ZENKOKU RINGYO KAIRYO FUKYU KYOKAI (2001).

costs–such as the direct and indirect operating expenses associated with each machine, forest-road establishment expenses, and regeneration expenses–were estimated (Eq. (1)).

$$A = D + I + F + R \quad (1)$$

A: All costs, D : Direct operation expenses, I : Indirect operation expenses, F : Forest-road establishment expenses, R : Regeneration expenses

Labor expenses associated with forestry-machine operators and other forestry workers were set at 1,683 yen/hour, and labor expenses associated with truck drivers were set at 2,400 yen/hour (SAWAGUCHI, 1996). Direct operating expenses are shown in Table 2. Direct operation expenses included labor expenses and machinery expenses (maintenance expenses, management expenses, depreciation expenses, and fuel and oil expenses). For yarders, direct operation expenses included setting and removal expenses, supplies expenses. For forwarder and skidder, direct operation expenses included spur road establishment expenses.

Landing-establishment expenses, machine and worker transportation expenses, task-manager expenses, garage-maintenance expenses, overhead costs, incidental personnel expenses, and handling fees associated with the log market were considered as indirect operation expenses (ZENKOKU RINGYO KAIRYO FUKYU KYOKAI, 2001). We assumed expenses of road establishment

between landings and their nearest existing roads to be 45,000 yen/m based on physiographic conditions (KOBAYASHI, 1997) when there were no road grids in the subcompartments. This study did not consider the subsidy for road establishment.

Regeneration expenses included site preparation, planting, weeding, vine cutting, pruning, and forest inventory (Table 3 and 4). This regeneration expenses was estimated by labor expenses and each operations necessary number of people, non-personnel expenses, and insurance expenses (OKAWABATA, 2003). This study considered the subsidy for regeneration. Subsidies were estimated with standard unit prices, areas, assessment coefficients, and the subsidy rate of Tochigi Prefectural Government. The subsidies were estimated at 2,082,000 yen/hectare for Japanese cedar and 2,070,000 yen/hectare for Hinoki cypress, respectively.

Extraction of Production Forests

If the revenue was larger than all cost for each subcompartment, the subcompartment was assumed as a production forest candidate. In addition to the estimation conditions mentioned above, to examine the sensitivity of the estimations, the sensitivity analyses were conducted with various cutting ages such as 80, 100, 120 years and log prices assumed to be dou-

Table 3 Japanese cedar regeneration expenses (yen/hectare)

Operation	Japanese cedar regeneration expenses				
	Number of people	Labor	Insurance	Non-personnel	Total
Site preparation	20.768	205,042	2,969		208,011
Planting	16.531	163,211	2,363	288,382	453,956
Fertilizing	1.315	12,983	188	15,773	28,944
Supplementary planting	4.435	43,787	634		44,421
Weeding	85.748	846,590	12,259	4,548	863,397
Fallen tree raising	12.542	123,827	1,793		125,620
Vine cutting	3.325	32,828	475		33,303
Cleaning cutting	13.566	133,937	1,939		135,877
Pruning	30.505	301,176	4,361		305,537
Forest inventory	2.104	20,773	301		21,074
Protect and manage	7.855	77,552	1,123		78,675
Others	6.149	60,709	879	151,972	213,560
Total	204.843	2,022,415	29,285	460,675	2,512,375

Table 4 Hinoki cypress regeneration expenses (yen/hectare)

Operation	Hinoki cypress regeneration expenses				
	Number of people	Labor	Insurance	Non-personnel	Total
Site preparation	22.478	262,925	6,620		269,546
Planting	18.659	218,254	5,496	358,232	581,982
Fertilizing	1.296	15,159	382	18,385	33,926
Supplementary planting	2.819	32,974	830		33,804
Weeding	76.641	896,470	22,573	3,410	922,453
Fallen tree raising	8.839	103,390	2,603		105,993
Vine cutting	2.013	23,546	593		24,139
Cleaning cutting	12.485	146,037	3,677		149,714
Pruning	36.003	421,127	10,604		431,731
Forest inventory	3.109	36,366	916		37,282
Protect and manage	6.323	73,960	1,862		75,822
Others	7.164	83,797	2,110	140,060	225,967
Total	197.829	2,314,006	58,267	520,087	2,892,359

ble of the present log prices which was almost equal to the log prices in 1981.

RESULTS AND DISCUSSION

Results of extracting production forests with cutting ages in all subcompartments set to 60 years and considering all costs except regeneration costs are shown in Fig. 10. In almost subcompartments, costs surpassed revenues even without the regeneration costs. Therefore, only 10.04% of plantation forests were production forest candidates. According to the result with considering regeneration costs, only 1.93% was production forest candidates (Table 5). This could be the reason why 94% of the forests are classified as those intended for water and soil conservation instead of forests for resource cyclic use although Kanuma area is one of the famous forestry areas in Tochigi Prefecture.

To examine the sensitivity of the estimations on log prices, the estimation was conducted with log prices assumed to be double their level from 1981. As a result, 55.25% of plantation forests were production-forest candidates (Table 5). Hinoki cypress and a little Japanese cedar was extracted as a production-forest candidate in the case of current log prices, without taking into consideration regeneration costs (Fig. 11), while Japanese cedar was also extracted as a production-forest candidate in the case of double log prices with regeneration costs considered (Fig. 12). Therefore, this model could relatively accurately estimate a variety of revenues and costs according to log prices.

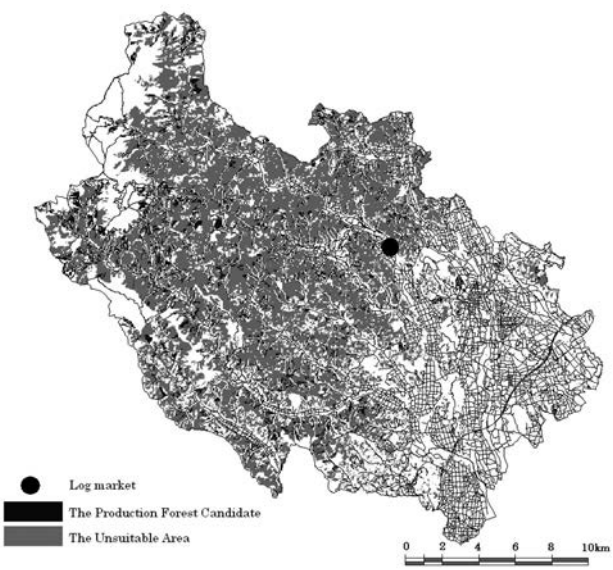


Fig. 10 The result with ages set to 60 years and considering all costs except regeneration expenses

Since revenues from clear cutting could not cover regeneration costs in almost subcompartments in this area on the current conditions, forest owners would not conduct planting operations even on unsuitable natural regeneration sites after clear cutting. Thus, the implication was that conducting sustainable forest management at cutting age, 60 years was difficult based on the current conditions in this area other than 1.93% stands. This situation spread in Japan, especially Kyushu Island (Tsuduki, 2006).

This situation occurred due to low log prices and high costs. Because log prices of Hinoki cypress were higher than those of Japanese ceder, Hinoki cypress and a little Japanese cedar were extracted as production-forest candidates without taking into consideration regeneration costs (Fig. 11). The Japan Forest Agency has conducted a measure on long-term rotation management because revenues from final cutting could not cover regeneration costs on the current conditions. Extending the cutting ages expected more revenues. Therefore, estimations that involved cutting ages set at 80, 100, and 120 years were conducted. However, the percentage of production-forest candidates increased a little, so this measure might not support sustainable forest management in this area (Table 5). This occurred because estimations were conducted changing ages from 60 to 80, 100, and 120 years, and, subsequently, volumes were adjusted as well. There was no change in the quality of logs, subsequently log prices. However, if larger-diameter logs can come from long-term rotation management, log prices could be increased, subsequently production-forest candidates could

Table 5 Result considering long-term rotation management

Final Cutting Age (year)	The Production Forest Candidate Percentage (%)	
	Comparing Revenue and All Cost except Regeneration Expenses	Comparing Revenue and All Costs with Regeneration Expenses
60	10.04	1.93
80	10.74	4.81
100	12.15	6.91
120	13.33	8.86
*60	55.25	50.95

**Result of assumed double log prices.

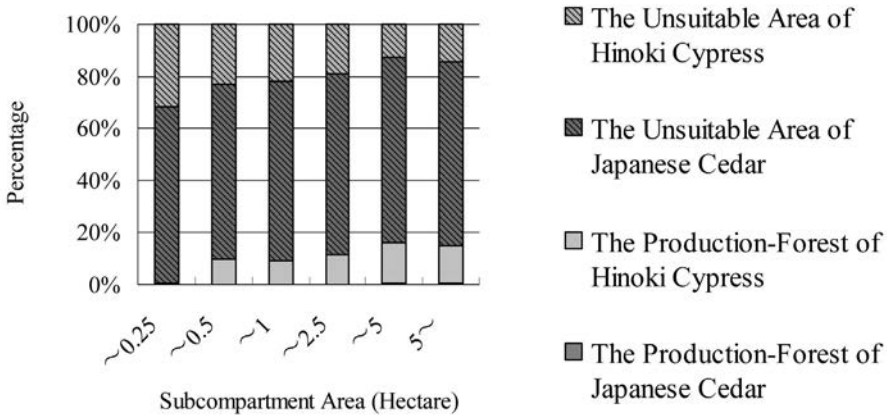


Fig. 11 The histogram of the result with ages set to 60 years and considering all costs except regeneration expense

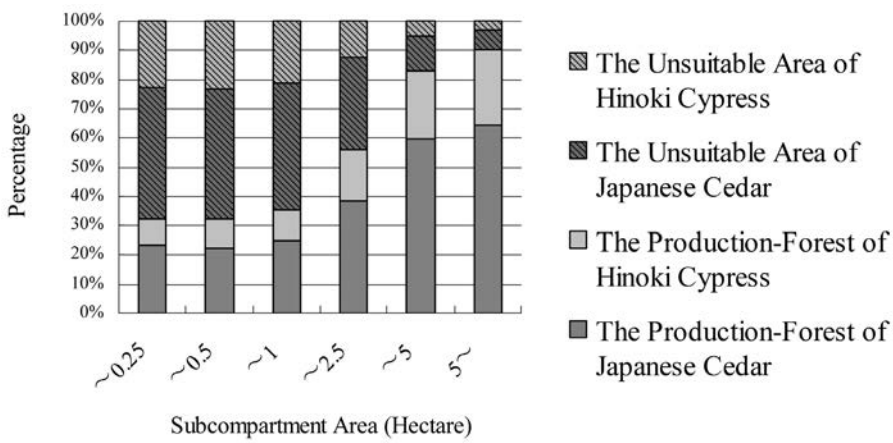


Fig. 12 The histogram of the result with ages set to 60 years, considering all costs, and double log prices

be increased greatly. Effect of changing log quality, subsequently log prices should be considered in the next study.

Because all costs included indirect costs which were almost all fixed costs, the smaller the volumes, the higher the costs. Therefore, all costs on smaller areas, subsequently volumes of subcompartments were much more expensive than log prices of even Hinoki cypress (Fig. 13). Both histograms (Figs. 11 and 12) showed the same trend in that few production forest candidates were extracted from the smaller subcompartment below 0.25 hectare (Fig. 11) and below 1 hectare (Fig. 12). Futhermre, Fig. 14 shows the cost components of the results with considering all costs. This finding indicated that the smaller the areas of subcompartments, the bigger the percentages of road-establishment expenses in relation to direct and indirect operation expenses. Thus, it will be necessary to decrease road-establishment costs considerably by developing forest-road networks and extending forestry-operation sites while merging small subcompartments. These findings could support the Japan Forest Agency's measure on extending operation sites by intensifying the merging of small subcompartments.

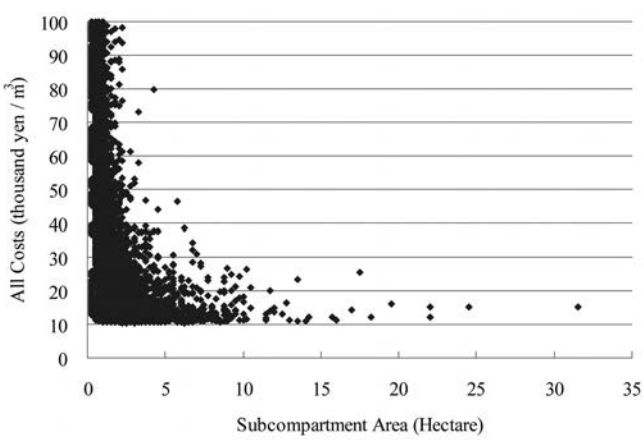


Fig. 13 Areas and all costs of subcompartments

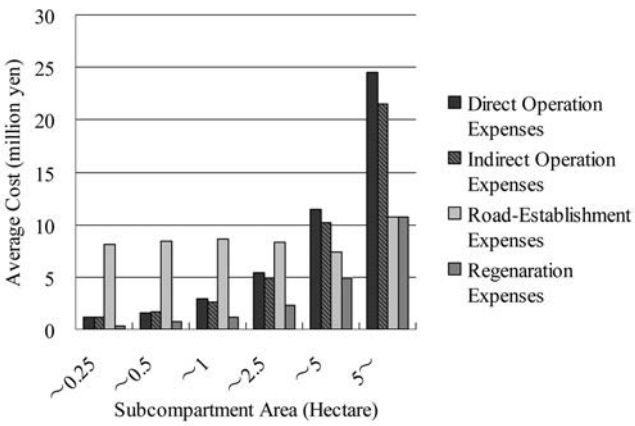


Fig. 14 Cost components

CONCLUSION

This study developed the method to extract production forests based on economic balances with considering regeneration expenses for sustainable forest management using forest registration and GIS data. From the results of the double log prices their level from 1981, this model could relatively accurately estimate a variety of revenues and costs according to log prices. According to the result on the current conditions with considering regeneration costs, only 1.93% was extracted production forest candidates. Thus, the implication was that conducting sustainable forest management at cutting age, 60 years was difficult based on the current conditions in this area other than 1.93% stands. This could be the reason why 94% of the forests are classified as those intended for water and soil conservation although Kanuma area is one of the famous forestry areas in Tochigi Prefecture.

This situation occurred due to low log prices and high costs. All costs on smaller areas, subsequently volumes of subcompartments were much more expensive than log prices of even Hinoki cypress because all costs included indirect costs which were almost all fixed costs, the smaller the areas, subsequently the volumes, the higher the costs. Therefore, it will be necessary to decrease all costs considerably by extending forestry-operation sites while merging small subcompartments.

However, this study did not consider effects of changing log prices along with log quality and some kinds of subsidies. Developing the forest-road networks and extending forestry-operation sites through the merger of small subcompartments should be also examined. The next study will analyze these effects and which factors have the ability to decrease costs. And in consideration of forest zoning based on this research, it is necessary to define appropriate places to consider not only costs but also forest function valuation.

ACKNOWLEDGMENTS

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Article

A Study on the Planning Method for Arborescent and Circular Forest Road Networks in Private Forest

Kaname Ito*, Ayami Murakami*, Masashi Saito*, Kazuhiro Aruga* and Toshiaki Tasaka*

ABSTRACT

In this study, the forest road network planning method for combining the arborescent forest road network and the circular forest road network was examined, and the road network planning program was made. First, the developed planning method for the forest road network selected the target sub-compartment which had the most benefits among sub-compartments. The benefits were calculated from the species, forest ages, yield tables, and log prices. After selecting the target sub-compartment, it determined an attainment point that is a terminal point of the arborescent forest road in the target sub-compartment. The target attainment point was the point to which the total distance from all grids in the target sub-compartment was minimized. Also, it determined the route of the forest road from the existing road to the target sub-compartment, using the Dijkstra method to minimize earthwork costs, where the gradient of the forest road was below 60%. Afterwards, it checked the route of forest roads from the target attainment point along the contour line, using the Dijkstra method where the gradient of the forest roads was below 35%, to develop the circular network. The program repeated these processes until the density of forest road network reached a predefined value. The road network program was able to plan the forest road network with different numbers of circular networks with the same density of the forest road network by changing the search range of forest roads along the contour line. Then, the development of forest road network and the skidding/yarding efficiency were evaluated. As a result, the average skidding/yarding distance on the forest road network developed by the program was shorter than that of the actual forest road networks constructed by a forest owner; the average distance between attainment points was also shorter than that of the actual forest road networks. Therefore, the program could plan forest road networks on which skidding/yarding efficiency and traffic benefits were improved.

Keywords: arborescent forest road, circular forest road, road network planning program, Dijkstra method, average pre-yarding distance

INTRODUCTION

For sustainable forest management and low-cost forestry operation, appropriate forest road networks have to be developed. There are two kinds of forest road networks. One is the arborescent network and the other is the circular network. The arborescent network is cost-effective because the skidding/yarding distance is efficiently shortened. However, the migration pathways from site to site for forest management activities such as monitoring and so on are limited and the migration distances are relatively longer. On the other hand, the circular network provides alternatives for migration pathways that improve the traffic benefits by shortening migration distances and by providing a detour in a time of disaster. However, the skidding/yarding distances are longer in a circular network. Therefore, it is important to balance the improvement of the skidding/yarding efficiency and the advantage of the circular network.

In research of road network planning, an examination of the theory of graphs (KANZAKI, 1966) and the research of automatic route design (SAKAI, 1981; KOBAYASHI, 1984) were carried out. Also, research of the circular road network formation algorithm (NITAMI, 1992; SAKAI and SUZUKI, 1993) and research of a prototype method for planning circular forest road network

Corresponding author: Kaname Ito
E-mail: kaname19860703@yahoo.co.jp
* Utsunomiya University, 350 Mine, Utsunomiya 321-8505, Japan

(KITAGAWA, 1993) were done. In addition, CHUNG *et al.* (2008) and STUCKELBERGER *et al.* (2006) researched forest road planning in foreign countries. However, little research on the balance between arborescent forest road and circular forest road has been done.

Our study purposed the forest road network planning method for combining the arborescent forest road network and the circular forest road network, and developed a road network planning program.

STUDY SITE AND MATERIALS

The study site is the western part of a privately-owned forest in Kanuma city, Tochigi prefecture, Japan (Fig. 1) at latitude 36°34″ N and longitude 139°32″ E and its elevation ranges from 500 m to 1,000 m. The forest area is about 230 ha. The density of forest road network in the forest is about 100 m/ha on the average. The forest road network is remarkably developed in this forest and a circular forest road network is formed.

The area of the study site is 97 ha (Fig. 2). The density of forest road network is about 130 m/ha. The vegetation is composed of Japanese cedar (*Cryptomeria japonica*), 50%, hinoki cypress (*Chamaecyparis obtusa*), 40%, and broad-leaved trees, 10%. The forest roads in this site were constructed in 1961 and 1977. The road network was afterwards rapidly developed to conduct thinning operations between 1995 and 2004. Thinning operations have been conducted in the forest along extended

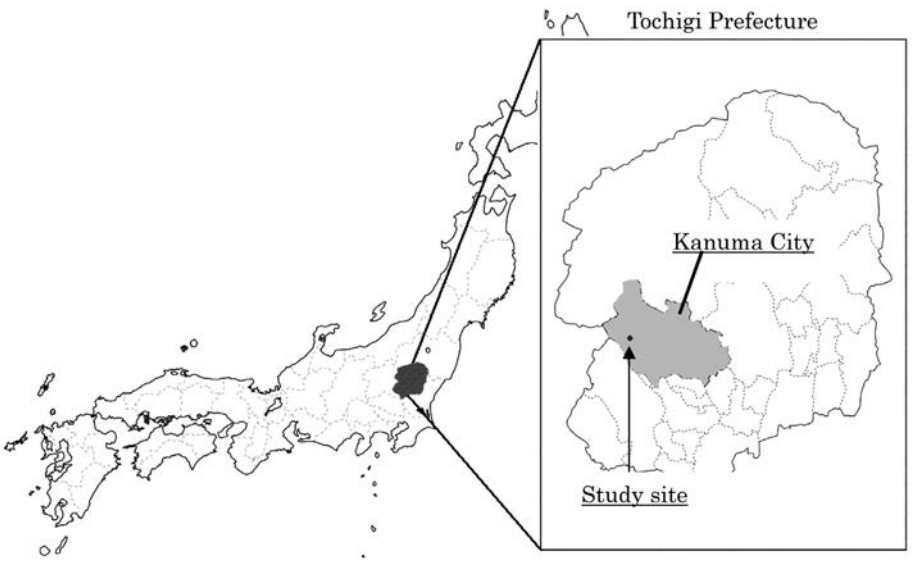

Fig. 1 Study site

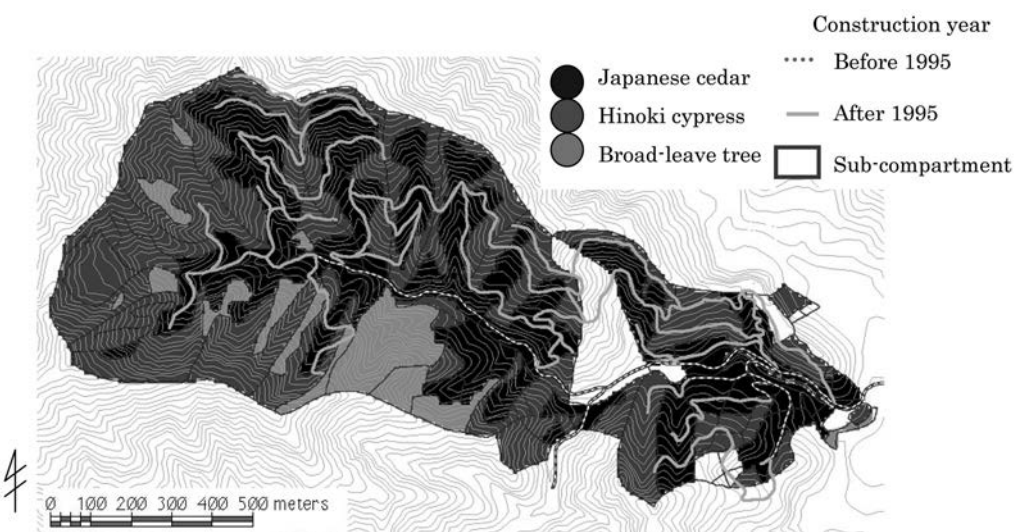

Fig. 2 Species and sub-cmpartaments of study site

roads. In this study site, roads orthogonal to the contour line were constructed first, and roads along the contour line were constructed afterwards. The logging method is chainsaw felling and processing, the grapple with the winch pre-yarding, and forwarder forwarding.

Forest-registration data (stand ages and tree species) and GIS data (sub-compartment layers) from the Tochigi Prefectural Government were used in the study, as were 10 m-grid digital elevation models (DEM) generated from the 1/5,000 topographic map of the Geographical Survey Institute. Contour lines were also generated 1/5,000 topographic map. Forest roads were measured with GPS. Data were converted into 10 m-grid raster data for consistency with DEM data.

DEVELOPMENT OF THE ROAD NETWORK PLANNING PROGRAM

In this study, the road network planning program for combining the arborescent forest road network and the circular forest road network was developed based on sub-compartments which were usual operational units in Japan and forest roads are planned from sub-compartments with the most benefits in turn (Fig. 3). First, the developed planning method for forest road network selects the target sub-compartment that has the most benefits among all sub-compartments. The benefits are calculated from the species (Fig. 2), forest ages (Fig. 4), yield tables (Table 1), and log prices. Log prices for Japanese cedar and hinoki cypress are set to 13,000 yen/m^3 and 25,400 yen/m^3, respectively (Japan Forestry Association, 2008).

After selecting the target sub-compartment, it determines an attainment point that is a terminal point of the arborescent road in the target sub-compartment. The target attainment point is the point to which the total distance from all grids in the target sub-compartment is minimized. It also determines the route of the arborescent forest road from the target attainment point to existing roads, or pre-planned roads after the second search, using the Dijkstra method (Dijkstra, 1959). The Dijkstra method is a technique of the route selection of which the evaluation function is minimized. In this program, the route with

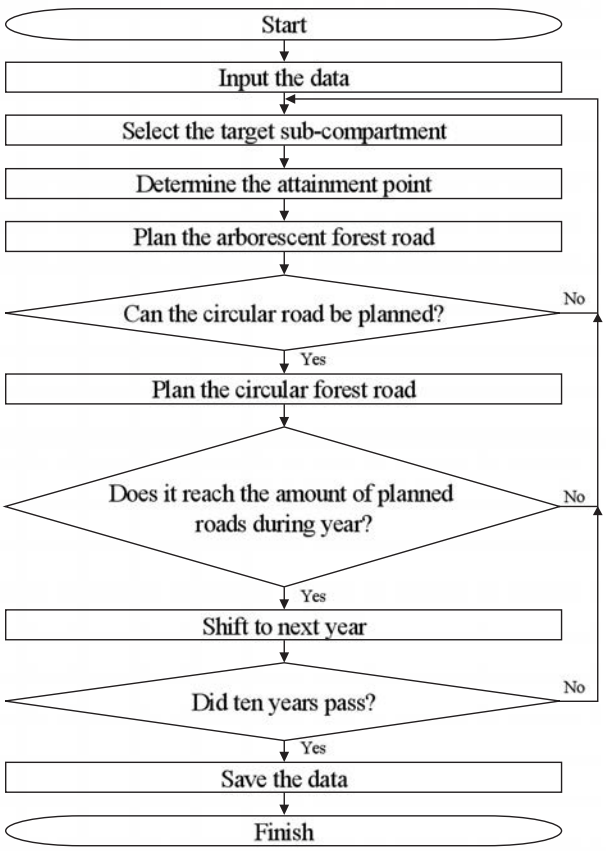

Fig. 3 Program flowchart

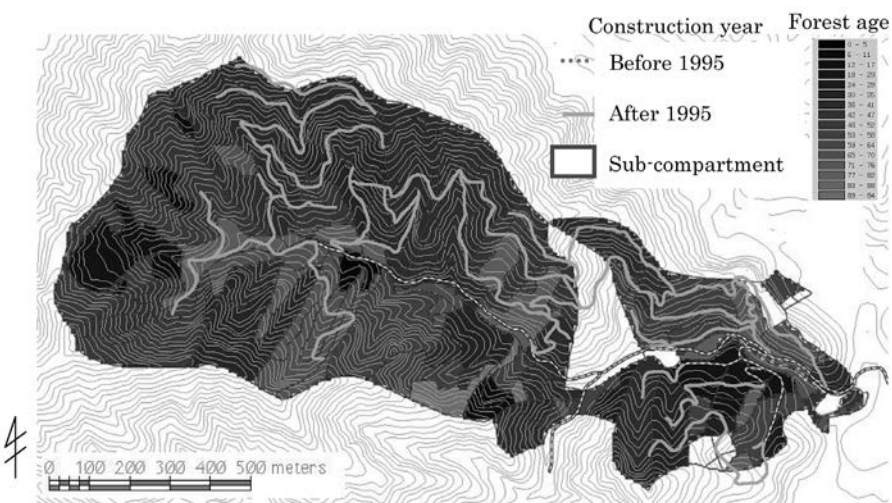

Fig. 4 Forest ages of study site (years)

Table 1 Yield table (m^3/ha)

age	Japanese cedar	Hinoki cyoress
30	295	194
40	375	270
50	445	320
60	515	360
70	575	385
80	625	396
90	670	406

minimum earthwork volumes where the gradient of the forest road is limited to below 60% is determined while repeating eight-neighborhood searches from the target attainment point. The earthwork volumes are calculated from the slope angles of cross sections and the assumptions such as road width: 2.5 m, right cut slope angles, and no fillings.

Afterwards, it checks whether a circular road along the contour line can be planned from the terminal point of the arborescent road to existing roads or pre-planned roads within the constant ranges of those elevations from ±1 m to ±5 m of the terminal point's elevation at an interval of 1 m, using the Dijkstra method to minimize distances, where the gradient of the forest road is limited to below 35%. If it is possible to connect circular roads, a circular road is added in the plan. The program repeats these processes until the length of planned roads exceeds the predefined length of forest roads in the simulated year. In order to execute the program, the limitations of forest road gradients were set to larger values such as 60% on the arborescent forest roads and 35% on the circular forest roads than those on actual forest roads due to the grid-based program.

SIMULATION OF FOREST ROAD NETWORK PLANNING

Method

Using the developed program, the forest road network planning was simulated for ten years, from 1995 through 2004, when the forest road network of the study site was developed rapidly. Therefore, the forest road constructed in 1961 and 1977

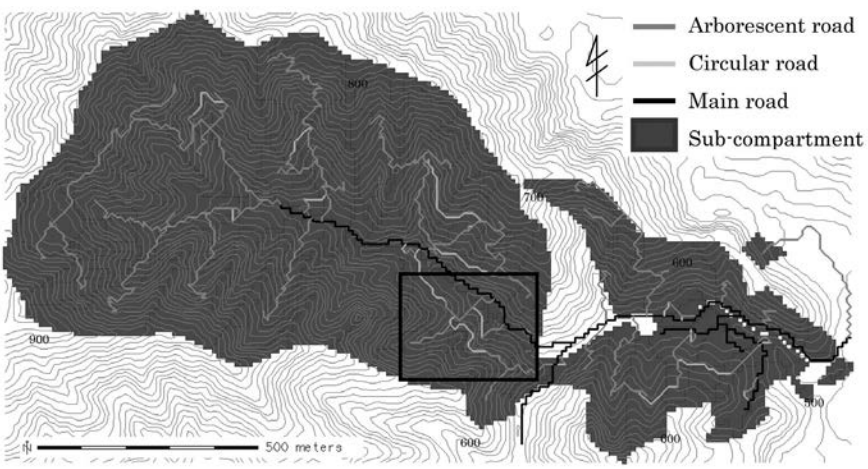

Fig. 5 Simulation result
Rectangle area is shown in Fig. 6 as extended figure.

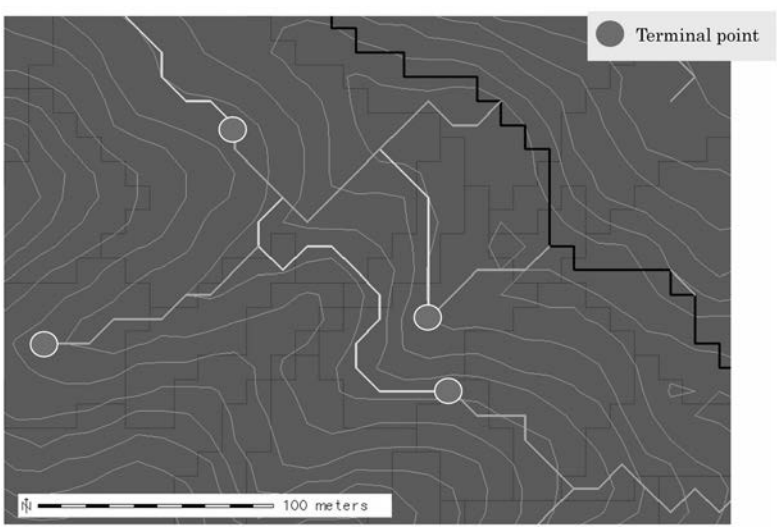

Fig. 6 Arborescent roads orthogonal to the contour line and circular roads along the contour line
This area indicated in Fig. 5 as rectangle area.

was assumed to exist. In the study site, the total length of roads constructed in the ten years from 1995 to 2004 was about 10,000 m. Therefore, the program plans for the construction of 1,000-m forest road every year from 1995 to 2004. Furthermore, since the theoretical density of forest road network was calculated at 167 m/ha from a rectangular model (Theoretical forest road density = 5,000 / maximum pre-yarding distance), by assuming the maximum pre-yarding distance to be 30 m (as a result of using a winch with a grapple-loader), the forest road network planning was also simulated until the density of forest road network reached 167 m/ha.

Results and Discussion

Fig. 5 shows the simulation result with the search ranges within ±5 m of the elevations of the terminal points of the arborescent forest roads. The actual forest road network has not been constructed in the southwestern part of the study area yet because of the young hinoki cypress planted in this area, which has not yet reached thinning age (Figs. 2 and 4). On the other hand, planned roads are widely spread in the study site except in the broad-leaved forests. Arborescent forest roads were planned to be orthogonal to the contour line, and circular roads were planned to be along the contour line (Fig. 6). The number of circular roads planned by the program was more than that of the actual forest road networks constructed by a forest owner (Fig. 7). The number of circular roads also increased as the search range was extended. Large circular forest road networks were constructed by the forest owner in the actual forest road network, and small circular forest road networks were planned in the forest road network by the program. Although the shapes of networks were different between actual

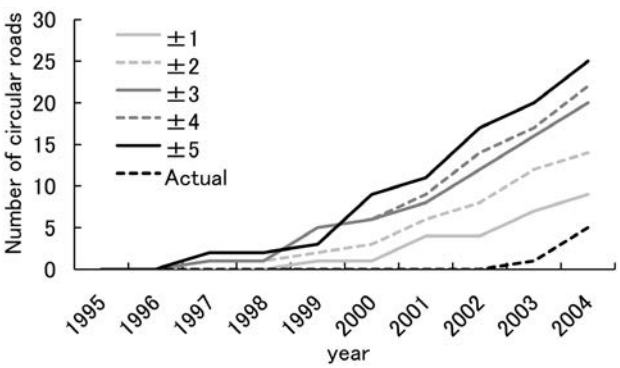

Fig. 7 Transition of the number of circular roads
Five kinds of planned forest roads with search ranges of circular roads from the terminal point of the arborescent road to existing roads or pre-planned roads between ±5 m at an interval of 1 m.

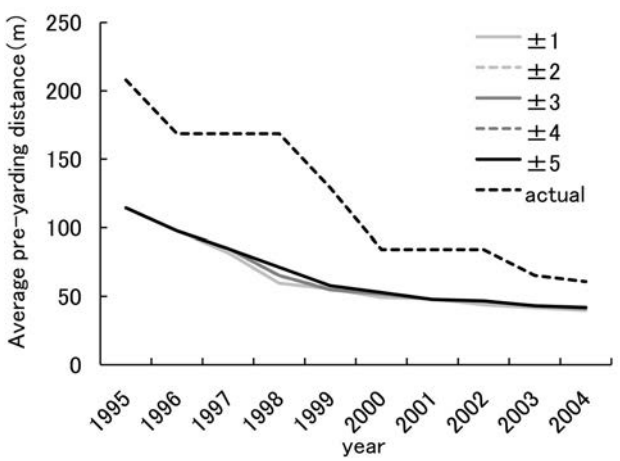

Fig. 8 Transition of the average pre-yarding distance
Five kinds of planned forest roads with search ranges of circular roads from the terminal point of the arborescent road to existing roads or pre-planned roads between ±5 m at an interval of 1 m.

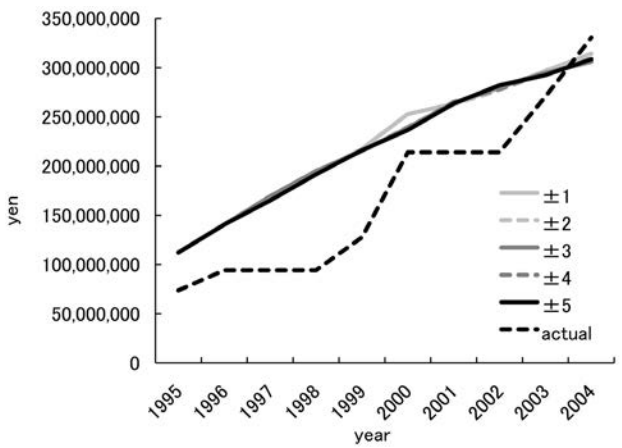

Fig. 9 Transition of expected benefits in pre-yarding capable areas
Five kinds of planned forest roads with search ranges of circular roads from the terminal point of the arborescent road to existing roads or pre-planned roads between ±5 m at an interval of 1 m.

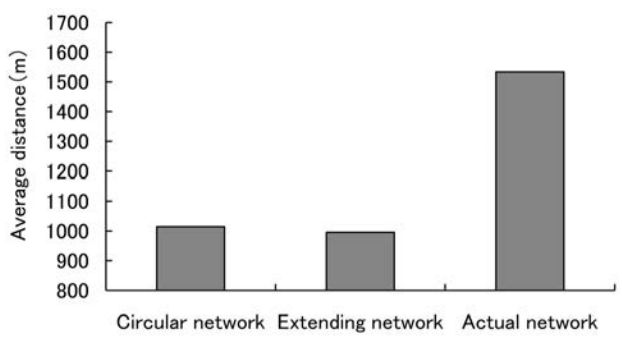

Fig. 10 Average distance between terminal points

Table 2 The values of the forest road networks

	actual	circular	extending
total forest road distance (m)	12,610	12,610	16,199
forest road density (m/ha)	130	130	167
number of circular roads	5	29	48
average pre-yarding distance (m)	61	44	39
average theoretical pre-yarding distance (m)	19	19	15
f value	3.2	2.3	2.6
ratio of pre-yarding capable area (%)	54	53	56
expected benefits(yen)	330,622,634	308,638,432	344,990,725

Average theoretical pre-yarding distance = 10,000 / (4 × forest road density).
f value = average pre-yarding distance / average theoretical pre-yarding distance.
Area of study site is 97 ha.

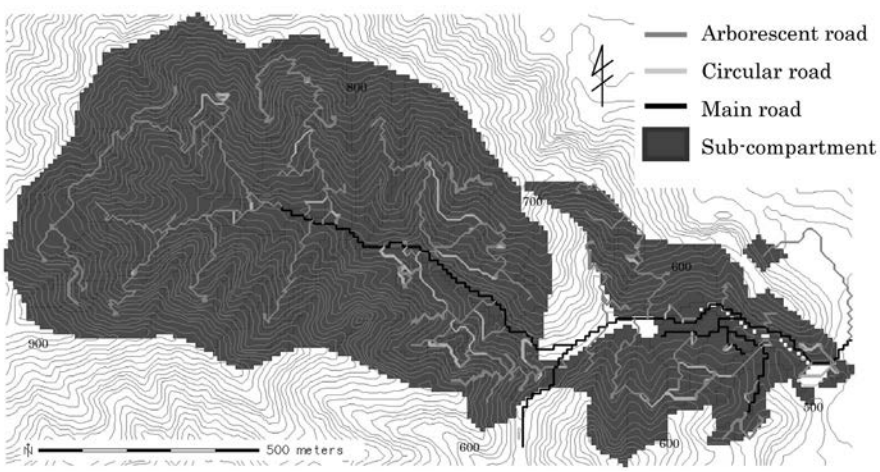

Fig. 11 The simulation result until the density of forest road network reached 167 m/ha
Thick lines are extended roads from Fig. 5.

forest roads and planned roads, the program planned the forest road network as intended.

The average pre-yarding distance of the forest road network planned by the program was shorter than that of the actual forest road network (Fig. 8). According to expected benefits in pre-yarding capable areas, which were assumed to be 30 m, the value of the forest road network planned by the program was more than that of the actual forest road networks except 2004 (Fig. 9). Moreover, the average distance between terminal points of the forest road network planned by the program was much shorter than that of the actual forest road network (Fig. 10). Therefore, logging operations on the forest road network planned by the program could be conducted more efficiently, and traffic benefits on the forest road network planned by the program were much higher than those on the actual forest road networks.

In addition, Fig. 11 shows the simulated result of extending forest roads until the density of forest road network reaches 167 m/ha which takes about three-and-a-half years. The number of circular roads and the ratio of pre-yarding capable area are higher, and the average pre-yarding distance and the average distance between terminal points of the forest road network are shorter than those in the forest road networks constructed by the forest owner and planned by the program for ten years (Table 2 and Fig. 10). However, the ratio of pre-yarding capable area increases by only 3% and f value is adversely increased compared with the forest road networks planned by the program for ten years (Table 2). This is because most of the circular forest road networks are very small (Fig. 11) although the number of circular roads increased much more than the forest road networks planned by the program for ten years.

CONCLUSIONS

In this study, the forest road network planning method for combining the arborescent forest road network and the circular forest road network was examined, and a road network

planning program was developed. This program could plan forest road networks with different numbers of circular roads while the density of forest road network was the same as that of actual road network. Also, a forest road network combining the arborescent forest road network, which is steep gradient, and the circular forest road network, which is gradual gradient, could be achieved. However the program planned a lot of small circular road networks while the large circular road networks were constructed in the actual forest road network. Therefore, more studies need to be conducted on the circular road network formation algorithm.

In the program, the circular forest roads were planned from the terminal point of the arborescent forest roads although the circular forest roads were actually constructed at a certain interval. Moreover, the forest roads were sequentially planned from the sub-compartments that had the most benefits among all sub-compartments. However, the order of sub-compartments might not be the best. Therefore, more studies on the starting points of circular roads and the method of determining the order of target sub-compartments have to be conducted.

Traditionally, forest roads, including the roads in the study site, were constructed along the valleys in Japan, and the circular forest road was constructed from these points. Nowadays, forest roads in other places are constructed on ridge tops that don't collapse easily. Therefore, it is necessary to consider terrain features like ridges and valleys for forest road planning.

ACKNOWLEDGEMENT

We sincerely appreciate Mr. Tadashi SAITO for providing the study sites.

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Article

Data Fusion Based Multi-Sensor System for High Accuracy Forest Management

Juergen Rossmann*, Michael Schluse*, Christian Schlette*, Arno Buecken*, Petra Krahwinkler* and Markus Emde*

ABSTRACT

In order to meet the needs of society's increasing demands for forest products in the coming years, sustainable forestry must become more efficient. Therefore, we propose to bring aerial and terrestrial survey technologies into the forest, as well as virtual production strategies, which are well-established in manufacturing. Precise position information of forest work machines and individual trees are necessary for a highly accurate navigation in the forest. As GPS does not provide the required accuracy, especially under a closed canopy, we propose a new localization approach based on a multi-sensor system. The approach will help to preserve the forest health while raising efficiency and enables applications based on highly accurate position information. The first part of this article gives a review on common localization strategies. The next part introduces the components of the sensor system in detail. In the third part the underlying principles are clarified and examples are given of how these are applied to new applications in forestry. The results are evaluated and compared to conventional measurement techniques.

Keywords: localization, navigation, forest machines, geographic information system, sensor framework

INTRODUCTION

In the last decade, automation revolutionized processes in forest management. Wood harvesters and forwarders enable faster logging operations on wider areas and with less manpower. On the one hand, this leads to lower costs and better price performance ratio of the timber extractions. On the other hand, it is still impossible to create or to execute logging orders based on precise information of single tree positions. Furthermore, usage of this heavy machinery compresses the forest soil and should be reduced to a minimum to decrease damages.

The Global Positioning System (GPS) has been introduced as the standard location service in forestry applications although the degree of accuracy is too low to identify a single tree. Signal absorption in the canopy and multi path effects within tree groups yield poor results and the error in measurement increases up to 50m and more. Thus accurate identification and localization of single trees, as well as optimized navigation planning for the machinery, is not possible using GPS. This leads to inefficient processes in the logging operation.

Today, a common method to prepare a timber extraction starts with a forest manager manually marking the trees to cut. Based on this on-site information, a logging operation order is generated for the stand. The machine operator locates the stand and executes the logging operation. Localizing the marked trees depends on the cooperation and understanding of the forest manager and the machine operator. Furthermore the overall experience of the machine operator in planning and executing logging operations is a main factor of time and cost effective wood harvesting (Purfürst and Erler, 2007).

Approaches to identify single trees or to localize forest work machines with a higher accuracy have been implemented and tested beforehand, for example with Differential GPS (DGPS) by Georgsson *et al.* (2006) and Miettinen *et al.* (2007). We conducted comparative tests to identify single trees permanently and repeatable carried out with high-performance DGPS receivers, for instance with receivers used on construction machines or in the precision agriculture sector. These tests did not show satisfactory results. A series of tests with DGPS

Corresponding author: Markus Emde
E-mail: Emde@mmi.rwth-aachen.de
* Institute of Man-Machine Interaction RWTH Aachen University Ahornstr. 55, 52074 Aachen, Germany

receivers mounted on wood harvesters even showed worse results – resulting in the total loss of any signal while shifting under canopy. Furthermore the use of correction signals takes the existence of special hardware and the availability of such services for granted. As this cannot be guaranteed everywhere, it is no real option.

Improvements on localization with best results can be reached combining several sensor technologies. PURFÜRST *et al.* (2007) presented an approach combining GPS, odometry and radar technology for localization and navigation algorithms. Since it is based on odometry, slipping wheels and drift on the forest ground as well as on slopes can sum up to unacceptable errors while the GPS receiver submits wrong or no position information.

Progress in the field of identifying single trees from airborne laser scanner data in combination with satellite data is the starting point of our approach (ROSSMANN and BÜCKEN, 2007). The underlying algorithms allow us to identify single trees and to generate a global tree map with a mean position error of 0.5 to 1.5 m. All trees having a diameter breast height (DBH) bigger than 0.2 m are stored in a database with their derived parameters like position, DBH or tree type providing the basis for an advanced forest management tool. The approach has been proven on 3 test areas with a total size of approximately 800 km^2.

Combination of this information and derived data from the local sensor framework of a forest machine allows us the development of new applications in the forest such as highly accurate self localization of machines as well as the navigation planning in consideration of ecological and economical aspects. As it is necessary to identify the tree that has been cut, precise geo-referenced information on the position of the harvesting head is given in addition.

SENSORS

In this part we introduce all sensors mounted on the wood harvester which was constructed as a prototype for such a forest machine.

External Sensors

Sensors measuring aspects of the external environment contribute to the position estimation of the forest machine. As all sensors determining the geo-referenced position are located on the cabin, it is used as the base of all further calculations for geo-referencing the vehicle, the crane and the harvesting head. Estimating the geo-referenced position of the harvesting head depends on the kinematic chain from the cabin to the wood harvester's head.

Laser Scanners

A so called local tree map (Fig. 1) is generated by LIDAR technology (LIght Detection And Ranging) and compared to a global tree map (Fig. 2). The importance of the local tree map is explained in the section *VisualGPS* later in this article.

Laser scanners emit pulses of laser rays and objects in the surrounding area of the scanners reflect the emitted rays of light. The distance is determined from the time-of-flight – the time between the transmission and detection of the rays of light. From this data a point cloud is created describing the shapes of the objects surrounding the scanner.

Both 2D and 3D scanners are available, but in order to build a low-cost system, 2D scanners were preferred in this work. Besides this, the rough environment was taken into account.

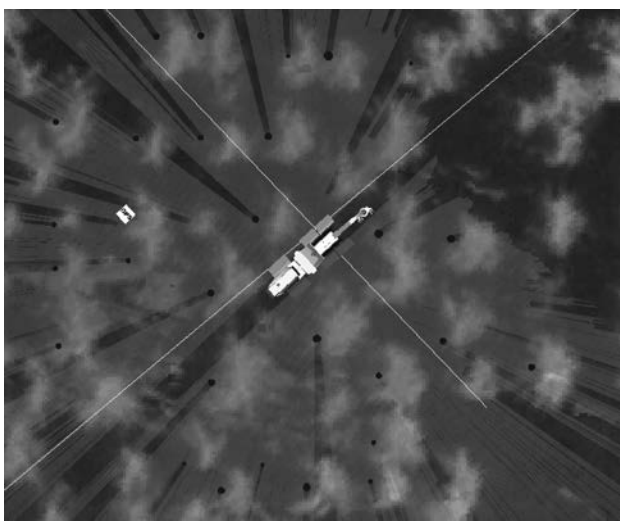

Fig. 1 Visualization of the forest machine (model in the center), laser rays (lines radiating from the harvester), trees of the local tree map (dark grey dots causing "shadows" in the laser ray visualization) and representation of the GPS (as white cube) in 2D-view in our simulation software

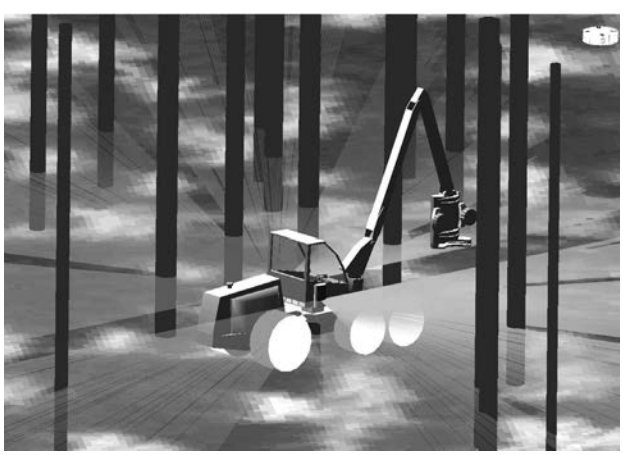

Fig. 2 Visualization of the forest machine, the laser rays as well as the local and global tree map (lying on top of each other) in 3D

Resistance to humidity, temperature variations and dust as well as vibrations and shocks were further criteria in favor of robust 2D laser scanners.

The laser scanners were mounted on the right and left side of the cabin, each of them covering an area of 180° to each side of the wood harvester cabin (Fig. 1 and Fig. 2). Attaching them to the cabin has several reasons. First of all, the cabin has an elevated position relative to the ground. This leads to better scan results because the understory and other objects which are not of interest stay below the scanner plane. Furthermore the danger of damaging scanners mounted on the cabin is reduced since they are safer from getting hit by stems and branches as well as by tree resin.

To get a local tree map of adequate resolution, the laser scanners allow for a horizontal resolution of 0.125°. The rotation frequency can be increased up to a value of 10 Hz. In comparison, a GPS receiver normally updates its position with a frequency of 1 Hz.

Table 1 shows the characteristics of the scanners in use.

Global Positioning System Receiver

A low-cost GPS receiver was added to the wood harvester's sensor framework. As described in the introduction, such receivers suffer from inaccurate position information in the forest. Still, the results are good enough to estimate the location of the forest machine as an entry-point for the following algorithms and it accelerates the high accuracy localization of the wood harvester.

The antenna of the receiver has been attached on the top of the cabin. Here, signal occlusion from the wood harvester itself is reduced to a minimum and the possibility of getting a sufficient number of satellites is increased.

Table 1 Characteristics of the scanners in use (SICK, 2008)

Max. scanned distance	250 m
At 10% remission	2.5 − 80 m
At 20% remission	2.5 − 114 m
Effective scan angle	Up to 300°
Angular resolution	0.125° to 1.5° in 0.125° steps
Scanning frequency	Single frame/5 to 10Hz in steps of 1 Hz
Measurement resolution	3.9 mm (1/256)
Systematic Error	+/− 38 mm at 20% to 90% remission
Statistical error	30 mm at 20% to 90% remission
Beam divergence	2.8 mrad (0,160°)
Laser class	1 (eye safe)
Enclose rating	IP 67
Operating temperature	−25 ℃ to +50 ℃

The receiver in use is known for its ability to acquire and maintain position information fast and independent from its environment (SIRF, 2007). In our tests, it was possible to get rough position information under densely covered tree groups.

It is based on a 20 channel architecture and supports WAAS and EGNOS. Furthermore it allows for more than 200,000 correlations for an accelerated time-to-first-fix within less than one second. This is relevant when a signal loss occurs. Subsequent to this event a fast re-localization can be performed.

Compass

A 3-axis compass with tilt compensation was integrated in the cabin of the wood harvester to determine the cabin orientation (PNI, 2007). This information reduces the number of steps for refinement in the *VisualGPS*-algorithm.

A test series has been carried out to find an optimum position for shielding the compass from external influences. Such a position was found directly under the windscreen. Here the magnetic environment is stable enough for steady sensor data and influences from the electro magnetic fields of the engine are minimized.

Internal Sensors

A set of internal sensors determine the position of the harvesting head relative to the geo-referenced position of the cabin following the kinematic chain from the cabin to the head (Fig. 3). The first sensors measure changes of position of the cabin. Actual angles of the cabin's tilt and rotation are provided. These sensors as well as the sensor to measure the rotation of the crane are build-in sensors by the manufacturer and are only mentioned briefly.

The cabin can be tilted in two directions. Tilting is used to level the cabin when the wood harvester itself is not levelled. This can be done automatically by the wood harvester's on-

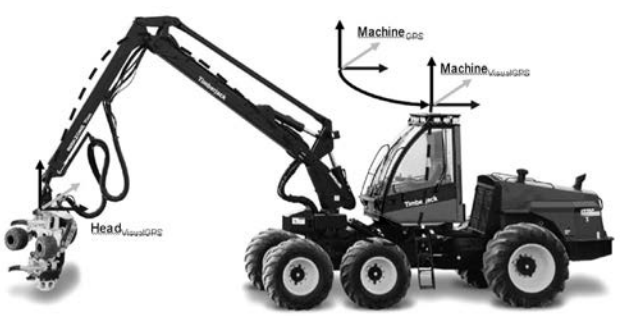

Fig. 3 Drawing of the kinematic chain of the wood harvester from cabin to harvesting head
In addition the shifting of the GPS position measured and the calculated improved position of the VisualGPS.

board software. Manually disabling this feature is possible but it is often enabled by the machine operator for higher comfort. Sideways a tilt of 15° is possible, whereas forward and backward tilting is limited to 11° (DEERE & COMPANY, 2007).

In addition to tilting, the rotation of the cabin is adjusted to the rotation of the crane. If for example the machine operator rotates the crane to the left, the cabin is also rotated to the left so that the operator can directly see the harvesting head. Like the tilting of the cabin this function can be disabled or a tilting or rotating angle can be set manually. A cabin rotation of +/−50° is possible (DEERE & COMPANY, 2007).

The next sensors on the kinematic chain are the sensors to determine the frame tilt and roll. Here, two-axis inclinometers have been chosen and mounted into the frame of the wood harvester (for detailed information see NOKIA (2008)). For the use in rough environment, this inclinometer is designed to be nearly immune to vibration and shocks and is enclosed in a high durable casing.

The aforementioned rotation of the crane is determined by a built-in sensor which was equipped to the wood harvester by the manufacturer. Software interfaces are provided by the manufacturer to retrieve data from these sensors with high accuracy.

The position and orientation of the harvesting head relative to the crane base depend on the extension length of each hydraulic cylinder of the crane. Cylinders originally mounted on the wood harvester were replaced by new ones[1] having linear position transducers integrated which measure the actual extension length: Two cylinders at the bottom responsible for the tilt of the crane, two cylinders executing the lift and jib rotation and one cylinder responsible for the extension of the crane. By drilling out the rods the patented sensor system[2] could be integrated. Tests regarding the mechanical strength of the new cylinders showed increased performance when compared to the original, older model cylinders.

The linear transducers were connected to the CAN-BUS network via converters and transmit the sensor data to a second onboard computer.

Fig. 4 Harvester at KWF meeting 2008

The prototype of this wood harvester has been presented at the KWF meeting 2008 in Schmallenberg, Germany (Fig. 4).

APPLICATIONS

VisualGPS (Forest Machine Localization)

GPS based localization and navigation in the forest suffers from low position accuracy and even signal loss resulting in wrong position estimations. Therefore a new approach to determine the position of a vehicle was implemented recombining new developments in the field of mobile robotics with methods estimating single tree positions from aerial survey data.

A wood harvester equipped with the mentioned sensors to measure aspects of its environment is able to determine its position with higher accuracy by fusing this data and recombining it with information of a global tree map provided by the approach mentioned in ROSSMANN and BÜCKEN (2007). Matching the local sensor data of the forest machine against this data of the global tree map allows for highly accurate self-localization.

The first step is to generate a local tree map (Fig. 1) from the point cloud data of the mounted laser scanners. Filter algorithms eliminate unusable data such as points at infinity and sparse points to reduce the number of tree candidates.

Afterwards, a feature extraction algorithm determines positions of circular objects in the local coordinate system of each laser scanner and calculates its diameter. Two algorithms have been implemented. First one is based on convolution, comparing circular shapes.

A second algorithm based on Fast Hough Transformation by GUIL *et al.* (1995) has been implemented in addition and is highly scalable for multi-core processors or can be performed on graphics hardware if supported. Therefore, point cloud data of each tree hypothesis is used and evaluated in Hough space.

Detected objects represent trees in the surrounding environment and the combination of these trees with their positions result in the local tree map of the forest machine.

Subsequent to the object recognition process a matching algorithm is started using the preprocessed global tree map as well as the dynamically generated local tree map. This calculation is based on a particle filter algorithm as described in THRUN *et al.* (2005). Since a single tree as a landmark cannot be associated with its corresponding tree in the map, patterns of

[1] Cylinders were manufactured by Pacoma GmbH, Germany.

[2] Sensor system was developed by Rota Engineering Ltd., GB.

tree positions are matched.

In the algorithm each particle represents a hypothesis for the position of the forest machine and is tested for its probability to represent the searched position. At first generated particles are distributed uniformly with an importance weight w_t on a square-cut area, which is assumed to be the target area (Fig. 5). Without a rough estimation of the harvester position, the search has to be performed on the complete global tree map area, resulting in a much larger number of particles required to generate a reliable position estimation. By using an imprecise position estimation provided by GPS, the area of interest can be narrowed.

Trees close to this area are extracted from the global tree map and are used to recalculate the importance weight w_t of the particles in each sampling step. Since not only the location of the forest machine is unknown, but also its orientation, the heading has to be estimated along with the position.

Therefore the probability measure used in the propagation step was enhanced. Instead of using only the distances of the trees, their relative position is used, considering the heading φ_t of the current particle t:

$$w_t^{[m]} \propto \sum_{treegroup} \min_{treecandidates} \left| \begin{matrix} |(x_{tree,\,rot}-x_R)|-|(x_{candidate}-x_t)|+ \\ |(y_{tree,\,rot}-y_R)|-|(y_{candidate}-y_t)| \end{matrix} \right| \quad (1)$$

with $x_{tree,\,rot} = x_{tree} \cdot \cos(\varphi_t) + y_{tree} \cdot \sin(\varphi_t)$

and $y_{tree,\,rot} = -x_{tree} \cdot \sin(\varphi_t) + y_{tree} \cdot \cos(\varphi_t)$

where $x_{tree,\,rot}$ and $y_{tree,\,rot}$ represent a local tree position measured by harvester's scanner rotated by the angle of current particle. x_R and y_R define a reference point from which the distances of the local trees are measured and $x_{candidate}$ and $y_{candidate}$ represent the position of the current tree candidate taken from the global map. x_t, y_t and φ_t describe the position and angle of the particle *t*. Finally, *treegroup* represents the group of trees detected in harvester's scanner data and *treecandidates* the trees taken from the global tree map on the square-cut area which is assumed to be the target area.

The rotation variant approach directly calculates the heading of the vehicle, but the sensibility towards rotation, which results from the new probability measure, leads to a higher number of particles which have to be used during the initialization step. To avoid high calculation times the number of particles has to be reduced using a compass, providing information on the heading of the forest machine. Furthermore, the number of trees, for which the distance has to be calculated, is reduced. Trees with a distance from the initial pose estimation X_{GPS} below the sum of the estimation of the maximal position error and the maximal distance of the trees in the scanned tree group from the reference position are extracted from the tree map.

$$|X_{candidate} - X_{GPS}| < r_{error} + \max_{treegroup} |X_{tree} - X_R| \quad (2)$$

with $X_{candidate}$ representing a candidate free taken from the

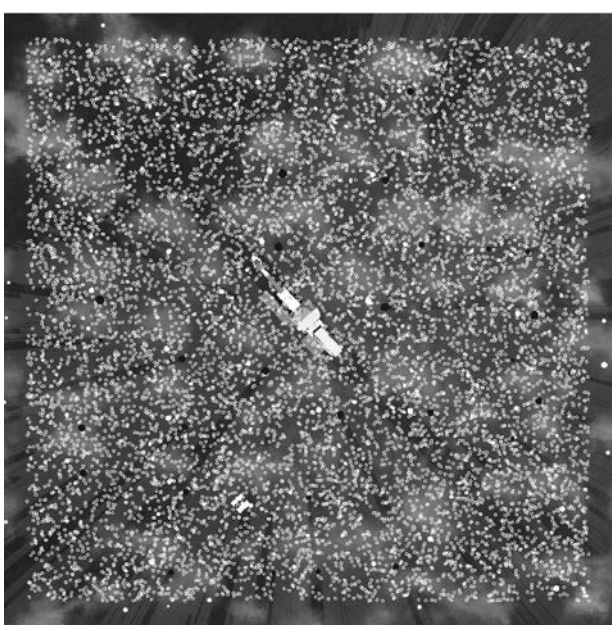

Fig. 5 Visualization of particle filter initialization; particles (white rings) are distributed on target area
Additionally the forest machine (in the center) and the laser rays as well as the trees (dark grey dots represent local tree map, light grey dots the global tree map) are shown.

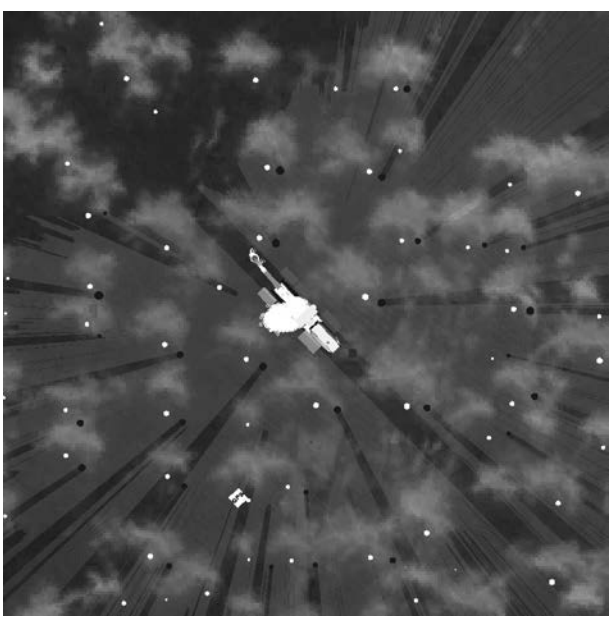

Fig. 6 Visualization of particle concentration during resampling step
Particles (white rings) accumulate near left edge of the cabin front of the forest machine. Moreover the laser rays and the global (light grey dots) and local trees (dark grey dots) are visualized.

global map and X_{GPS} as the initial pose estimation. Furthermore, r_{error} marks the estimation of the maximum position error. In addition, X_{tree} and X_R represent a local tree position measured by the harvester's scanner and the reference position to which the measurements of the trees are related. Finally, *treegroup* represents the group of trees detected in harvester's scanner data.

In the following step the evaluation threshold for the particles is decreased. Particles with high importance weight are eliminated and new ones are generated and positioned randomly around the remaining ones. This leads to an accumulation of particles at the best position estimations (Fig. 6 with an interim result, but already accumulating close to the crane base of the wood harvester). The resampling steps are repeated until the particles accumulate in one point.

On standard PCs cycle times for the *VisualGPS* approach of 0.5s were reached. Fig. 7 shows the several processing steps and data sources as a diagram.

To evaluate the accuracy of the system a surveyor's office was instructed to compare the vehicles position at 7 distinct locations to ground truth data. At each position the sensor input data was written to file for several seconds. This data was evaluated and for each location and more than 45 pose estimations were calculated. The differences of the calculated and the measured positions are shown in Fig. 8. A mean error of approximately 0.55 m was measured.

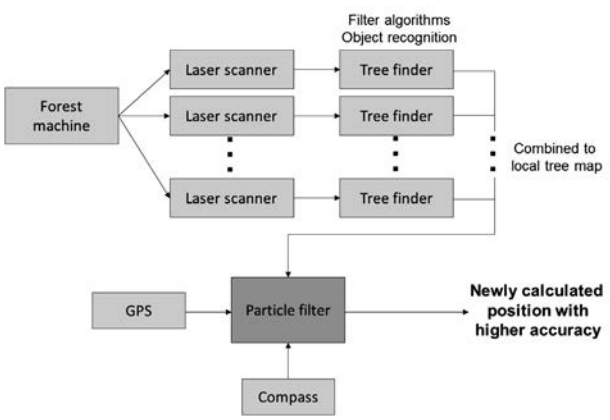

Fig. 7 Workflow diagram of processes and data sources of *VisualGPS*

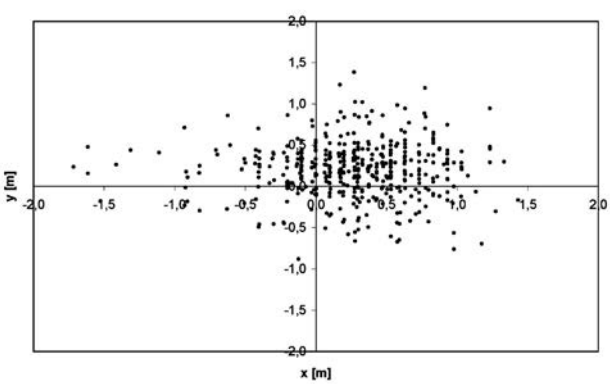

Fig. 8 Results of position deviation of *VisualGPS*
A mean error of approximately 0.55m was measured.

The *VisualGPS*-approach has been presented at the KWF meeting 2008 in Schmallenberg (Germany) (Forbig and Encke, 2008) and has been described in detail in Rossmann *et al.* (2008a) and Rossmann *et al.* (2009). Furthermore the *VisualGPS*-approach was one of the regional winners of the European Satellite Navigation Competition 2008 (Rossmann *et al.*, 2008b).

Geo-Referenced Logging Operations (Localization of the Harvesting Head)

Using the additional sensors aforementioned, the position of the harvesting head relative to the cabin can be determined in geo-referenced coordinates. Localizing the forest machine with high accuracy gives only rough information on the position of the harvesting head, as the crane has a large work space. As it is vital in some regions or countries to identify single trees that have to be cut or to track trees that have been cut for accounting, the aforementioned sensor system provides highly accurate position information.

Combining the information of tilt angles, rotation angles and extension length of the cylinders as well as the geo-referenced position of the cabin, the harvesting head is localized in geo-coordinates by interpreting the chain from the cabin to the harvesting head as a kinematic chain (Fig. 3). The position is determined by solving the forward transformation. The following equation determines the geo-referenced coordinates of the harvesting head relative to the cabin:

$$\begin{aligned} &T_{Head} = T_{MachineBase} \cdot T_{Inclinometers} \cdot T_{Crane} \\ &\text{with} \\ &T_{MachineBase} := T_{VisualGPS} \cdot (T_{CabinTilt})^{-1} \cdot (T_{CabinRot})^{-1} \cdot (T_{LaserScoffset})^{-1} \\ &T_{Crane} := T_{CraneRotation} \cdot T_{CraneTilt} \cdot T_{CraneLift} \cdot T_{CraneJib} \cdot T_{CraneExtend} \end{aligned} \quad (3)$$

where T_{Head} represents the resulting tranformation matrix of the harvesting head. It results from $T_{MachineBase}$ which represents the transformation matrix of the undercarriage, $T_{Inclinometers}$ representing the transformation matrix of the chassis tilt and T_{Crane} describing the displacements and rotations of the crane. $T_{MachineBase}$ and T_{Crane} are put into concrete terms using the transformation matrices describing each displacement and rotation in this substring of the cinematic chain.

The logging operation itself can be planned semi-automatically. Trees to cut are selected in the simulation system and a felling indicator is added. Information is transferred to the on-board computer system of the wood harvester. Having performed the timber extraction, all data of the logging operation can be transferred back to the database. Afterwards reporting and accounting can be performed.

A test series was carried out to determine the accuracy of this sensor system. The harvesting head was navigated to dif-

ferent positions. Camparing these measurements to measerements simultaneously performed with traditional equipement, a mean error of approximately 0.2 m was noticed.

Combining the results of the *VisualGPS*-approach and the sensor equipped crane, localization of a single tree is possible with a mean error of 0.75 m. The approach was presented at KWF meeting 2008 in Schmallenberg (FORBIG and ENCKE, 2008).

Taking these results into account, identification of single trees, which were cut, now becomes possible. This means that logging operations can be planned in total different way in the future.

Single Tree Navigator

Giving the machine operator the logging instructions with geo-referenced trees to cut, the operator is able to navigate to a single tree, to grasp it, cut it and to deposit it next to the skid road. Furthermore piling for each tree owner is no longer necessary. Based on the correct measurements of the harvesting head and information on the geo-referenced tree, accounting for each tree owner is possible.

Being able to localize the wood harvester as well as to determine the position of a single tree to be cut, a navigator (Fig. 9) was implemented.

This navigator supports the machine operator and calculates an optimized route to all trees to be cut and included in the logging operation. Trees with a felling indicator are marked in red. Other ones are marked black. Furthermore skid roads are symbolized by dark grey lines and a light grey area around the skid roads displays the work space of the crane. As the forest machine is localized with high accuracy, leaving the skid road out of tolerance can be detected and a warning can be displayed. This helps to prevent damage to the forest soil.

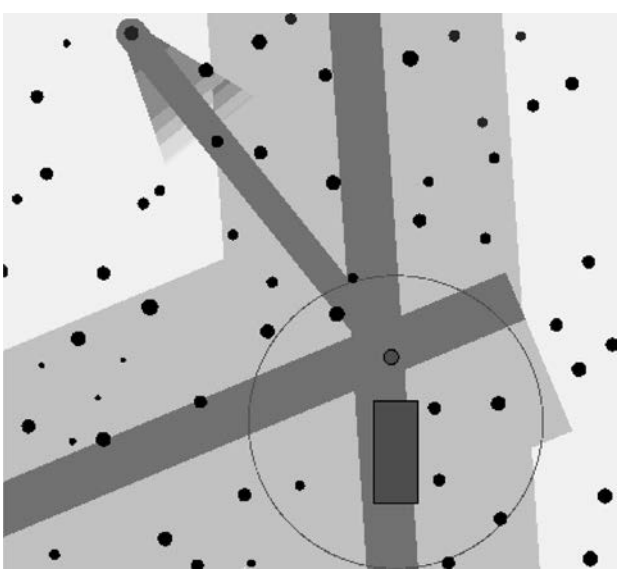

Fig. 9 Simple navigator for logging operations
The arrow indicates the next tree to cut for an optimized logging operation. The rectangle represents the forest machine; the mid grey lines are symbols for skid roads. The circle around the forest machine shows its actual working area; the light grey areas besides the skid roads give an indication of the working area in general. In addition the surrounding trees (black dots) and the actual position of the aggregate (circle with dark grey filling in front of the forest machine) are visualized.

Terrestrial Acquisition of Trees and their Attributes

Furthermore an approach to determine tree parameters like diameter breast height was implemented. Combining the digital terrain model and the information on pose and orientation of the laser scanner, a height of scan profile from the ground can be calculated. This information is used with parametrisized taper functions to derive the DBH (Fig. 10) and other information.

Approaches based on airborne laser scanner data, for example described in ROSSMANN *et al.* (2007), derive parameters like the DBH from extracted tree height and knowledge on tree type etc. This implementation verifies the derived data, using sensor information of the terrestrial laser scanners. The approach will be enhanced providing parameters for local adjustment functions, thus resulting in single trees extraction from airborne laser scanner data with higher accuracy.

Furthermore, single trees are detected, which could not be delineated from airborne laser scanning data, because they were shadowed by canopy of the surrounding trees. This is a starting point to merge information of the global tree map with information of the local tree map on assured facts.

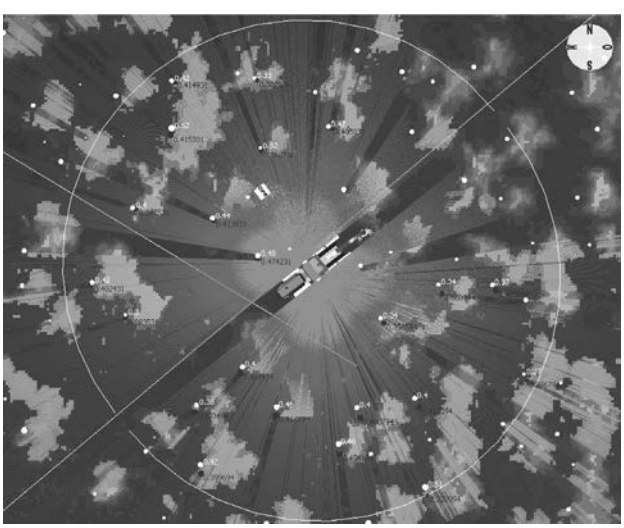

Fig. 10 Visualization of DBH estimation for stand inventory
Values delineated from airborne laser scanner data (values in light grey) and terrestrial laser scanner data (dark grey) are shown in comparison. Furthermore the known scene as shown i.e. in Fig. 6.

Forestry vehicles equipped with a sensor framework as mentioned in this paper are furthermore able to perform permanent forest inventories. In contrast to approaches only using airborne laser scanner data, this approach allows a continuous data collection with up-to-date information of the stand at low cost.

CONCLUSION AND FUTURE WORK

Taking into account the results of the presented applications, localization of a wood harvester and identification of single trees are now possible. Based on this sensor framework new applications and algorithms were implemented. For example the introduced single tree navigator allows optimized logging operations on wider areas, as well as on very small-sized ones. It supports the machine operator by identifying the next tree to cut and enables a correct accounting for the tree owner. Furthermore it helps reducing damage to forest soil, because the forest machine performs the logging operation in an optimized way.

To enhance the reliability of the tree detection algorithm a detailed digital ground model combined with information on the cabin tilt can be used to detect areas where rays of the laser scanners hit the ground and false detection of trees in these areas could be avoided. Furthermore the position of the harvesting head and the crane could be taken into account, ignoring them in the laser scanner measurements as well.

In addition the algorithm can be tuned for better performance by reducing the number of particles needed. Integrating the algorithms of *VisualGPS* with a Kalman filter as described in Thrun *et al.* (2005) should increase the performance as well.

Augmenting the navigator with additional information, the machine operator can be supported in different ways. Further implementations could show trafficability of a skid road or information on the slope. Further work has to be done in the field of parameterization of the algorithm to determine single tree parameters from terrestrial laser scanner data. Actually, this tool supports only a few tree types. The correctness of the results must be determined in the future by performing several test series.

ACKNOWLEDGEMENTS

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Article

Segmentation and Classification with Discriminant Analysis of QuickBird Multispectral and Panchromatic Data to Distinguish *Cryptomeria japonica* and *Chamaecyparis obtusa* Patches

Yasumasa Hirata[*1], Naoyuki Furuya[*2], Atsushi Sakai[*2], Tomoaki Takahashi[*3], Yoshio Awaya[*4] and Toru Sakai[*5]

ABSTRACT

Stands of *Cryptomeria japonica* and *Chamaecyparis obtusa* have different functions: in particular, diversity of understory vegetation and prevention of soil erosion, but their distribution is not always delineated and distinguished on forest maps. This study investigated the relationship between parameters in the image segmentation procedure for high-resolution satellite data and generated object size in object-oriented classification, and distinguished objects of *C. japonica* and *C. obtusa* by means of discriminant analysis. Thirty-six sample plots were established in *C. japonica* and *C. obtusa* stands in the national forests of the Koisegawa watershed. QuickBird panchromatic and multispectral data was used for this study. Segmentation, which is the first step in object-oriented classification, was applied to the image data of the sample plots, and species were assigned to corresponding objects generated from the image segmentation. For these objects, the average and standard deviation of digital number for the four multispectral bands and panchromatic band and the Normalized Difference Vegetation Index (NDVI) were calculated within them. Discriminant analysis to distinguish *C. japonica* and *C. obtusa* was conducted using these twelve variables of average and standard deviation as independent variables. The correct distinction was made for 100% of *C. japonica* objects and 95.5% of *C. obtusa* objects. The results clarified that it was possible to distinguish *C. japonica* and *C. obtusa* patches using high-resolution satellite data.

Keywords: *Cryptomeria japonica*, *Chamaecyparis obtusa*, high-resolution satellite data, object-oriented classification, scale parameter

INTRODUCTION

In Japan, forests cover an area of about 25 million ha and this estimate has remained stable for 40 years. This constancy of forested area is the result of the balance between decreased forest area by development due to expansion of urban areas and increased area by afforestation and/or reforestation on abandoned farmland due to people moving from the mountains down to the towns. However, the ratio of plantation to natural and secondary forest area has varied greatly. The increase in timber demand for reconstruction after World War II resulted in the conversion of natural forests to sugi (*Cryptomeria japonica*) and hinoki (*Chamaecyparis obtusa*) plantations in Japan, and the continuous natural forests became segmented (MAFF, 2003). Secondary forests near urban areas finished their role of providing fuel and many of them were also converted to plantations. As a result, 42% of the forested area or 28% of the total land area is now covered with plantations (FAO, 2006), forming a mosaic of natural or secondary forests,

Corresponding author: Yasumasa Hirata
E-mail: hirat09@affrc.go.jp
[*1] Bureau of Climate Change, Forestry and Forest Products Research Institute, 1 Matsunosato, Tsukuba, 305-8687, Japan
[*2] Forestry Division, Japan International Research Center of Agricultural Sciences, 1-1 Ohwashi, Tsukuba, 305-8686, Japan
[*3] Department of Forest Management, Forestry and Forest Products Research Institute, 1 Matsunosato, Tsukuba, 305-8687, Japan
[*4] River Basin Research Center, Gifu University, 1-1 Yanagido, Gifu, 501-1193, Japan
[*5] Research Institute for Humanity and Nature, 457-4 Motoyama, Kamigamo, Kita-ku, Kyoto 603-8047, Japan

plantations and clear-cutting areas. Restricted movement of animals and loss of biodiversity and genetic diversity are a growing concern.

In Japan, the Forest Agency and local governments have prepared forest maps at the scale of 1:5,000 and forest registers by sub-compartment as management units concerning forest distribution and attributes such as location, area, species, stand age, stand volume and regulation. Advances in computer technology as well as improved GIS functions in the past several years have led to the expansion of GIS utilization. The rapid construction of GIS data related to forest management units, which was generated from these forest maps and forest registers, has provided additional spatial understanding, and demonstrates great ability for planning forest road construction and final cutting. However, some species are occasionally recorded for a sub-compartment in the forest register because *C. japonica* and *C. obtusa* were planted in respectively suitable sites on a slope, and some broad-leaved trees are found along the valley or the ridge. While the mixed proportion is recorded in the forest register for such a sub-compartment, the information on species distribution is not delineated on the forest map. Stands of *C. japonica* and *C. obtusa* have different functions: in particular, diversity of understory vegetation and prevention of soil erosion; therefore, the spatial understanding of their distribution is important.

In the application of remote sensing to forestry, forest type mapping is essential in terms of sustainable forest management and ecological conservation, and has been required first and foremost since the launch of the first Earth observation satellite. Conventional remotely sensed data, such as from Landsat and SPOT satellites, has been used for forest type mapping making use of the difference in reflectance properties of the forest canopies (for example, Woodcook *et al.*, 1994; Jiang *et al.*, 2004; Gjertsen, 2007). However, there has been an issue about the mixture of different forest or land-cover types in a pixel leading to misclassification in the case of a complex forest stand shape or small stand area in comparison with the pixel size of remotely sensed data.

The new generation of commercial high-resolution satellite data with ground resolution finer than 1×1 m such as IKONOS and QuickBird opened a new era in digital analysis of forest stand attributes. High-resolution satellite data has almost the same spatial resolution as a conventional aerial photograph, and it is possible to use the image for interpretation as an aerial photograph. In addition, high-resolution satellite data has a wider dynamic range than conventional satellite data according to the degree of sensor sensitivity (Hirata, 2009). These advantages of high-resolution satellite data might make it possible to distinguish stands of different age and species. On the other hand, the irregularity of reflectance from the canopy surface appears within a domain where the reflectance property is regarded as uniform (Murakami, 2004), making it difficult to apply conventional pixel-based classification to high-resolution satellite data.

Recently, the new "object-oriented" classification method has been used instead of pixel-based classification. Object-oriented classification is effective in segmenting an area that consists of various land-cover types into objects with extensions of similar properties (Lamonaca *et al.*, 2008). Previous studies have applied this approach for land cover and forest mapping using conventional satellite data such as Landsat or SPOT (Geneletti and Gorte, 2003; Hall *et al.*, 2004; Bock *et al.*, 2005; Hay *et al.*, 2005; Conchedda *et al.*, 2008) as well as high-resolution satellite data such as IKONOS or QuickBird (van Coillie *et al.*, 2007; Lamonaca *et al.*, 2008; Martinez-Morales *et al.*, 2008). The object-oriented approach makes it possible to develop a classification strategy that employs spatial relationships between objects in addition to spectral information (Platt and Schoennagel, 2009).

The object-oriented classification approach consists of two procedures: image segmentation into objects and classification of generated objects. This study investigated the relationship between parameters in the image segmentation procedure for high-resolution satellite data and generated object size, and distinguished objects of *C. japonica* and *C. obtusa* by means of discriminant analysis.

MATERIALS AND METHODS

Study Area and Sample Plots

The study area was located in the Koisegawa watershed, Ibaraki prefecture, Japan (36°7′20″–36°19′21″N, 140°6′22″–140°18′55″E, WGS 84), which is an area of 235.5 km^2. The watershed is surrounded by Mt. Tsukuba, Mt. Ashio, Mt. Kaba, Mt. Nantai and Mt. Wagakuni, and farmland spreads out on the plain below 100 m above sea level. Orchards are found around the foot of the mountains, and natural forests, secondary forests and plantations are distributed north and west of the watershed, forming a mosaic pattern.

The national forests in the watershed, which are managed by the Ibaraki District Forest Office, were the targets of this study. These forests cover an area of 1,823 ha and plantations occupy 70% of the forests. The forests consist of plantations of *C. japonica* and *C. obtusa*, broad-leaved forests, mixed forests and small patches of conifer species.

A total of 36 circular sample plots of 0.04 ha each were established in the stands, which ranged in age from 15 to 93 years (Fig. 1, Table 1). Fourteen plots were set up in *C. japonica* stands and 22 plots in *C. obtusa* stands. The coordinates at the center of all sample plots were positioned by DGPS for superimposing on high-resolution satellite data. DBH of all standing trees in the sample plots was measured and species were recorded. Stand density in the sample plots was calculated from the number of standing trees per 0.04 ha. Mean DBH of sample plots ranged from 13.9 to 37.2 cm and stand density from 475 to 2,800 trees/ha. Tree height of more than 40% of the standing trees was measured in each sample plot and the others were

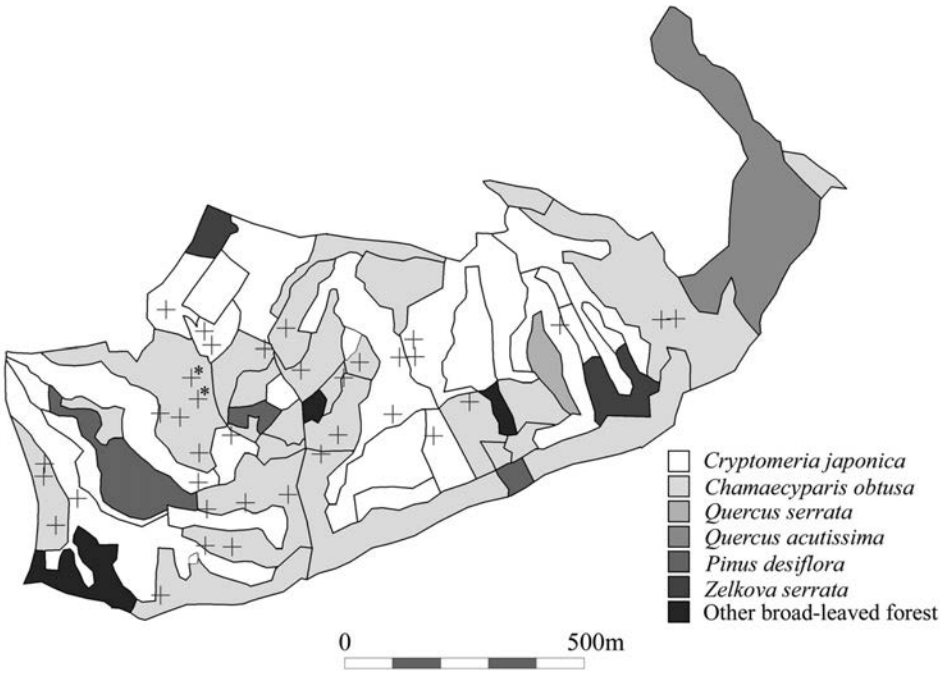

Fig. 1 Distribution of sample plots
Two plots of *Cryptomeria japonica* with asterisk (*) were located in the sub-compartment where *Chamaecyparis obtusa* was dominant.

Table 1 Number of sample plots by stand age class

Stand age class (years)	-20	21-30	31-40	41-50	51-60	61-	Total
C. japonica	2	0	4	3	4	1	14
C. obtusa	0	6	10	2	0	4	22
Total	2	6	14	5	4	5	36

estimated from the Näslund formula (NÄSLUND, 1936). The stand height in the sample plots varied from 9.6 to 24.8 m.

Satellite Data and GIS Data

QuickBird panchromatic and multispectral data was acquired on 27 February 2003. The spectral band of panchromatic data ranges from 450 to 900 nm, and the spatial resolution is 0.61 m at the nadir. Multispectral data consists of four separate spectral bands: blue (450-520 nm), green (520-600 nm), red (630-690 nm) and near infrared (760-900 nm), and they all have 2.44-m spatial resolution at the nadir (DIGITALGLOBE, 2006). The data was geo-registered to the Universal Transverse Mercator (UTM) coordinate system (WGS 84, Zone 54) with 0.7-m and 2.8-m spatial resolution, respectively, using the nearest neighbor method for resampling to maintain the original reflectance properties.

GIS data for the study area was generated from 1:5,000 forest maps and digital forest registers compiled by the Kanto Regional Forest Office to establish sample plots and confirm their stand age. This data was also used to geo-register QuickBird data using forest type information.

Image Segmentation

Segmentation in the object-oriented approach is characterized by the integrated use of spectral and textural information in comparison to the single use of spectral information in conventional pixel-based classification. We investigated the effect of the parameter concerning heterogeneity in segmentation in the object-oriented approach, on the number and average size of generated objects. The segmentation of high-resolution satellite data was conducted using eCognition software (DEFINIENS IMAGING, 2001) for object-oriented classification. The heterogeneity (f), which is defined as the addition of weighted values of the heterogeneity within the spectrum (h_{color}) and that within the shape (h_{shape}), is determined by the scale parameter in eCognition, and is expressed as below:

$$f = ph_{\text{color}} + (1-p)\,h_{\text{shape}} \quad (1)$$

where $0 \leq p \leq 1$ and is decided by the analyst. The scale parameter relates the minimum size required to identify a particular object, which depends on the resolution of the images.

There are two other parameters: the heterogeneity of compactness (h_{compact}) and that of smoothness (h_{smooth}), which are determined by the analyst. The heterogeneity within the shape is defined as the addition of their weighted values.

$$h_{\text{shape}} = q\,h_{\text{compact}} + (1\text{-}q)\,h_{\text{smooth}} \quad (2)$$

where $0 \leq q \leq 1$ and is decided by the analyst. We investigated the number and the average size of generated objects by scale parameter fixing h_{compact} and h_{smooth} to (0.1, 0.9), (0.5, 0.5) and (0.9, 0.1), respectively.

Extraction of Plantations

In the study area, there were several forest types such as plantations of *C. japonica* and *C. obtusa*, broad-leaved forests, mixed forests and small patches of conifer species. As the small patches of conifer species were found only around the top of the mountains, only the broad-leaved forests and mixed forests needed to be distinguished from the plantations. We prepared the high-resolution satellite data in the leafless season for the sake of facilitation. The Normalized Difference Vegetation Index (NDVI), which was one of the indices representing the condition of vegetation, was calculated from the red band (Band 3) and infrared band (Band 4) as below:

$$\text{NDVI} = (\text{Band 4} - \text{Band 3}) / (\text{Band 4} + \text{Band 3}) \quad (3)$$

NDVI was calculated for the study area using QuickBird multispectral data.

The average NDVI was calculated for each object generated by image segmentation. We used only those objects that were included in the sub-compartments of one forest type. QuickBird panchromatic data as well as multispectral data was used for image segmentation. The spatial resolution, namely pixel size, was different: 0.7 and 2.8 m. On the other hand, NDVI was calculated using multispectral data; therefore, some NDVI pixels within the boundary of objects included two different forest types. In this analysis, we used only NDVI pixels that were completely included in the objects to calculate the average. We compared the average NDVI by object in the plantations with that in the broad-leaved forests and mixed forests.

Discriminant Analysis

In Japan, *C. japonica* and *C. obtusa* trees are often planted in the same sub-compartment, and information on their distribution is not available. The distinction between *C. japonica* and *C. obtusa* patches was examined by means of discriminant analysis. Objects, which included sample plots, were used for this analysis. The average and standard deviation in digital number of panchromatic data and that of the four bands of multispectral data for these objects were calculated. The average and standard deviation of NDVI were also used for the analysis. We conducted the discriminant analysis using these twelve averages and standard deviations for each object as independent variables.

Test for Equality

While the forest type of generated objects can be confirmed by field survey, another method is required for the assessment of segmentation in comparison with the method for assessing the results of conventional pixel-based classification. Verification of the accuracy of pixel-based classification is conducted by pixel at a point where the forest type can be confirmed; however, in object-oriented classification, the boundaries of objects, namely the segmentation results, are important.

In Japan, forest management units consist of compartments and sub-compartments, and they are administered using forest registers and forest maps. Forest patches of the same forest type are normally smaller than a sub-compartment. The boundaries of these forest patches are not delineated in forest maps, but the proportion of each forest type in a sub-compartment is recorded in the forest registers from field observation. Therefore, the proportion of area by forest type obtained from the forest register and that obtained from object-oriented classification were compared by compartment. All objects for the study area that were obtained from image segmentation were classified into broad-leaved and mixed forests, *C. japonica*, and *C. obtusa* using the coefficients and constants of the linear discriminant function that were obtained in the above analysis. The total area of objects of the same forest type was generated by compartment. Finally, six compartments were used for the test for equality between proportions of area by species obtained from the forest register and those obtained from object-oriented classification in a compartment, and three compartments in the study area were excluded from the test due to cloud influence.

RESULTS AND DISCUSSION

Image Segmentation

The results of image segmentation with different scale parameters are shown in Fig. 2. From Fig. 2, it is obvious that the choice of scale parameter strongly effects on the generated object size. The relationship between scale parameter and the number of generated objects with different h_{compact} and h_{smooth} in image segmentation is shown in Fig. 3. The relationship between scale parameter and the average size of generated ob-

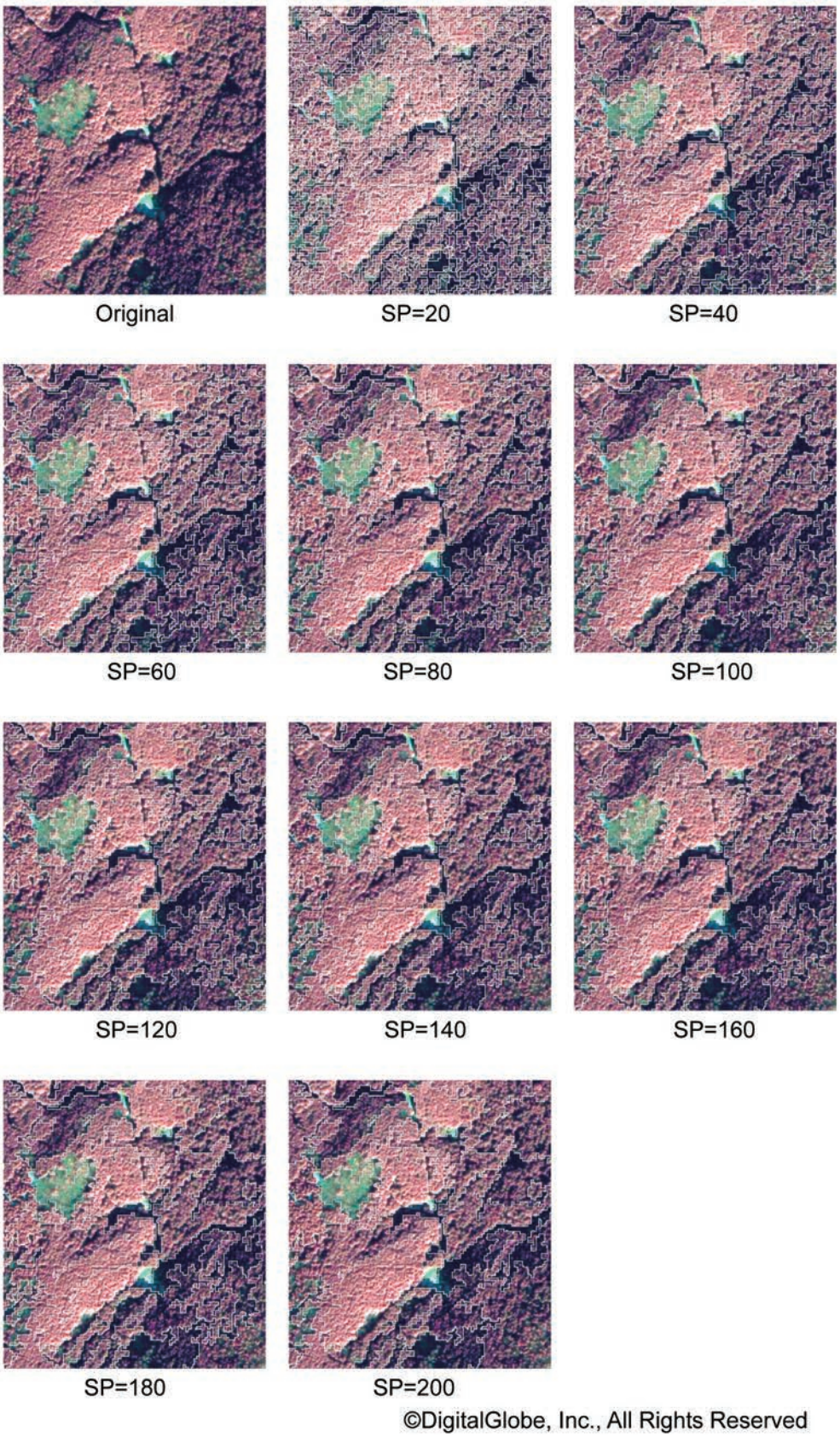

Fig. 2 Image segmentation with different scale parameters (SP)

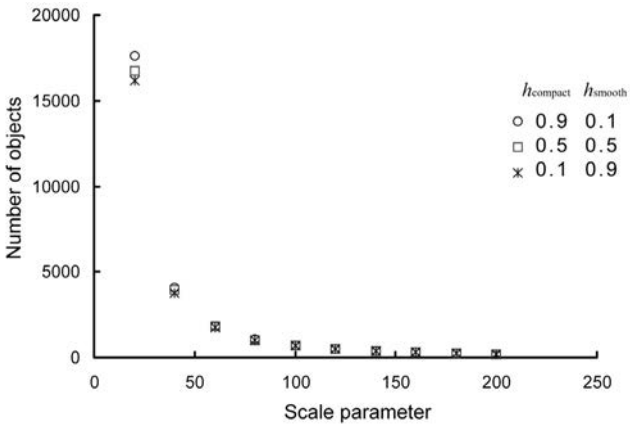

Fig. 3 The relationship between scale parameter and the number of generated objects with different $h_{compact}$ and h_{smooth} in image segmentation

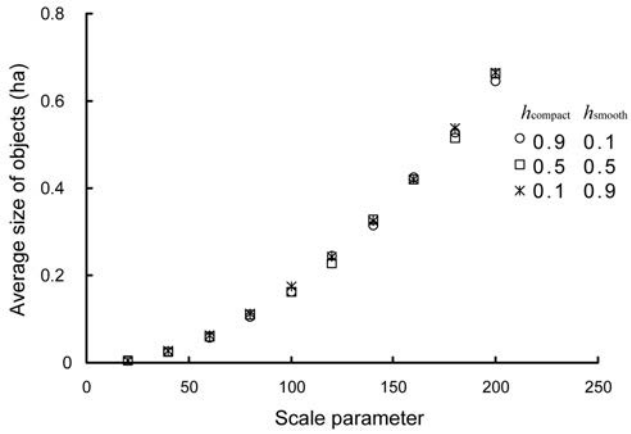

Fig. 4 The relationship between scale parameter and the average size of generated objects with different $h_{compact}$ and h_{smooth} in image segmentation

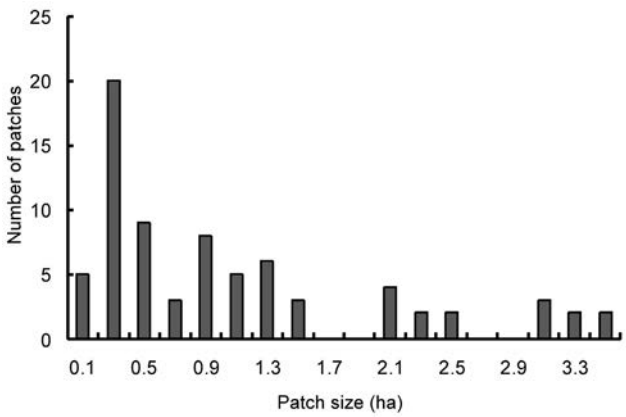

Fig. 5 The frequency of patch size consisting of one forest type in the study area

jects with different $h_{compact}$ and h_{smooth} in image segmentation is shown in Fig. 4. It is clear from these figures that different weight to $h_{compact}$ and h_{smooth} did not influence the average size or number of generated objects and only the scale parameter affected them. However, we should notice that these parameters influence the shape of generated objects.

The frequency of patch size consisting of one forest type in the study area obtained from the forest register, which was arranged from field investigation by foresters, is shown in Fig. 5. While the average was 1.2 ha, the mode was 0.3 ha. When the average size of generated objects was 0.3 ha, the scale parameter was between 120 and 140. Therefore, it is preferable that a smaller parameter than this, such as 100 or less, is used for extracting forest patches with an area of around 0.3 ha, and that patches smaller than 0.3 ha are integrated according to forest type.

When the scale parameter was 20, objects consisting of 10 to 20 trees in mature stands of *C. japonica* were generated by the image segmentation procedure. This number was rather smaller than the number that Awaya *et al.* (2007) obtained from IKONOS data using the same scale parameter. When the scale parameter was 40 to 60, mixed forest patches were reasonably extracted, but segmentation was observed for a plantation patch in the same stand. When the scale parameter was 80 to 100, segmentation of a plantation patch in the same stand was also found, as well as inequality in objects. However, results similar to the interpretation of high-resolution satellite image were obtained using these scale parameters. It was, therefore, considered that the segmentation using 80 to 100 for the scale parameter, with which a stand of the same forest type was divided into three to five objects, was practically applicable to forest type mapping using QuickBird data.

As forest patch size depends on the forestry practice and topographic conditions, the average size of forest patches consisting of one forest type should be estimated using the forest register, and a smaller scale parameter, with which objects smaller than average are generated, should be used for image segmentation. It is necessary to pay attention to the difference in generated objects using different sensors with different resolutions and different conditions for acquiring satellite data such as sun angle and sensor angle.

Nevertheless the effectiveness of image segmentation in object-oriented classification for extracting forest patches from high-resolution satellite data, it should be recognized that the results of segmentation do not often correspond to the boundaries of sub-compartments. These gaps result from the difference between segmentation of forest cover type derived from high-resolution satellite image and forest management unit. For example, it is difficult to segment image area which consists of multiple sub-compartments of same species with similar stand age. Therefore, the results of image segmentation cannot be used as substitution of forest GIS data concerning forest management unit. Mutual use of them is required to understand

Table 2 Statistics on Normal Difference Vegetation Index (NDVI) of objects in broad-leaved/mixed forests and plantations

Type	Number of objects	Mean	Standard Deviation	Maximum	Minimum
Broad-leaved/ mixed forest	64	0.44	0.14	0.56	0.23
Plantation	152	0.78	0.03	0.83	0.70

Table 3 The average and standard deviation (S.D.) of NDVI, multispectral and panchromatic data for the object in image segmentation which includes each sample plot

Plot	Species	NDVI		Band 1		Band 2		Band 3		Band 4		Panchromatic	
		Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.	Average	S.D.
2	*C. japonica*	80.2	3.1	156.0	3.8	178.1	7.8	85.1	6.5	295.0	65.7	283.9	79.4
12	*C. japonica*	78.0	5.1	155.1	3.3	173.4	7.9	82.2	6.4	248.2	57.5	247.9	68.2
13	*C. japonica*	75.9	6.6	150.9	3.4	165.7	7.6	76.5	6.2	184.9	49.6	207.7	59.3
21	*C. japonica*	76.2	6.3	155.1	4.2	172.9	8.8	82.6	8.1	233.8	59.6	241.2	69.7
22	*C. japonica*	73.9	7.2	154.7	4.3	171.7	10.1	80.7	8.3	207.3	68.0	222.4	71.4
26	*C. japonica*	78.6	4.9	155.5	3.0	175.4	6.5	83.3	5.5	260.8	51.8	255.2	64.6
29	*C. japonica*	77.5	4.1	154.0	3.5	171.2	7.6	79.8	5.9	220.5	53.0	226.4	66.6
30	*C. japonica*	78.2	3.2	155.4	2.8	175.3	7.3	83.3	5.8	256.4	54.2	254.3	66.3
31	*C. japonica*	79.0	2.4	156.7	3.3	179.4	6.2	87.2	4.7	294.8	41.1	283.8	58.0
32	*C. japonica*	76.0	5.9	154.6	3.5	172.1	6.9	81.5	6.5	223.5	48.1	229.5	60.0
33	*C. japonica*	78.0	5.1	155.1	3.3	173.4	7.9	82.2	6.4	248.2	57.5	247.9	68.2
34	*C. japonica*	78.0	5.1	155.1	3.3	173.4	7.9	82.2	6.4	248.2	57.5	247.9	68.2
36	*C. japonica*	77.6	5.2	153.5	4.1	170.9	10.0	80.4	8.0	228.5	73.5	234.8	78.9
37	*C. japonica*	74.7	8.2	155.0	4.1	170.9	8.3	80.2	7.3	210.1	62.1	226.0	69.3
1	*C. obtusa*	78.9	4.6	154.3	3.9	174.9	9.6	80.5	6.7	243.7	68.5	246.3	78.6
3	*C. obtusa*	81.1	2.1	161.0	2.5	196.8	6.7	97.0	3.6	422.4	49.2	360.7	65.1
4	*C. obtusa*	79.8	4.3	155.1	4.0	175.6	10.3	81.6	7.3	262.7	76.3	251.9	78.2
5	*C. obtusa*	83.1	1.8	159.4	3.6	190.0	6.4	92.9	4.5	426.5	44.5	367.1	67.9
6	*C. obtusa*	80.8	6.1	153.7	4.3	171.1	9.9	78.2	7.4	241.9	66.2	252.0	73.1
7	*C. obtusa*	81.5	3.2	160.5	3.8	190.6	8.0	94.7	8.5	405.9	56.4	354.3	67.4
8	*C. obtusa*	79.8	4.4	156.0	3.6	177.7	8.4	83.9	6.4	280.8	64.1	269.7	74.2
10	*C. obtusa*	79.8	4.2	156.3	2.8	179.3	6.4	85.1	5.0	290.8	48.6	273.9	64.9
11	*C. obtusa*	81.1	3.8	158.6	4.0	186.6	8.6	91.8	7.6	372.9	55.8	332.6	70.0
14	*C. obtusa*	68.0	9.9	167.1	6.2	199.2	11.2	108.3	12.1	322.3	76.7	311.3	77.3
15	*C. obtusa*	65.5	11.2	160.8	5.3	182.9	9.8	94.5	10.1	227.9	56.3	246.8	61.5
16	*C. obtusa*	79.8	5.1	151.7	3.6	165.4	6.9	74.0	5.3	191.0	49.3	206.9	63.6
17	*C. obtusa*	79.4	3.1	159.0	4.2	185.3	8.0	91.3	6.6	328.8	54.1	306.0	73.6
18	*C. obtusa*	82.3	1.9	160.3	3.2	193.1	6.2	96.1	5.3	435.7	53.8	369.3	76.1
19	*C. obtusa*	81.6	2.6	156.7	2.6	183.1	5.6	89.3	4.4	356.7	41.2	316.7	64.4
20	*C. obtusa*	80.6	4.2	155.4	3.2	177.6	6.8	84.9	5.3	299.7	53.8	281.8	72.8
23	*C. obtusa*	82.1	1.7	161.3	3.5	191.5	6.7	94.0	4.2	409.7	43.4	356.4	58.4
24	*C. obtusa*	81.3	2.4	158.3	3.3	182.8	5.9	86.9	4.7	331.4	42.6	305.2	59.3
25	*C. obtusa*	81.3	2.4	158.3	3.3	182.8	5.9	86.9	4.7	331.4	42.6	305.2	59.3
27	*C. obtusa*	81.1	2.6	157.4	3.2	182.1	9.4	86.8	6.4	325.2	68.3	306.1	82.4
28	*C. obtusa*	81.6	2.3	157.4	3.1	181.4	6.9	86.1	5.0	322.1	49.1	297.8	70.0
35	*C. obtusa*	77.2	7.7	155.2	4.1	177.2	9.8	82.3	7.6	247.8	68.7	250.0	79.1

present conditions of sub-compartment.

Extraction of Plantations

The frequency of NDVI for objects in broad-leaved/mixed forests and plantations is shown in Fig. 6 and the statistics are shown in Table 2. From Fig. 6 and Table 2, the maximum NDVI for objects in broad-leaved/mixed forests was 0.56, and the minimum NDVI for objects in plantations was 0.70. As a result, it was clear that objects in the broad-leaved/mixed forests and those in the plantations could be distinguished easily if the threshold for dividing them was set between the NDVI maximum in broad-leaved/mixed forests and the minimum in plantations when using the data from the leafless season.

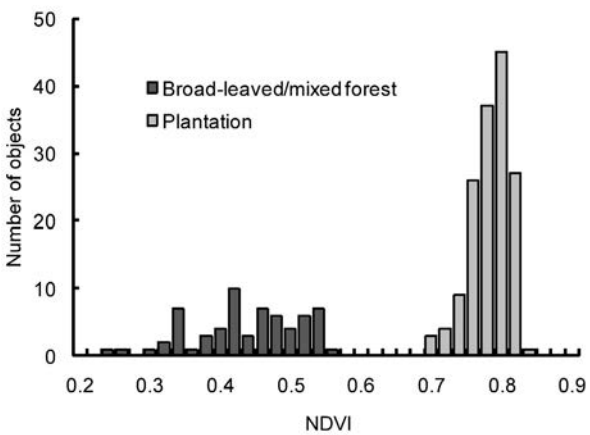

Fig. 6 The frequency of NDVI for objects in broad-leaved/mixed forests and plantations

Discriminant Analysis

The average and standard deviation (S.D.) of NDVI, multispectral and panchromatic data for the object in image segmentation, which includes each sample plot, are shown in Table 3. The results of discriminant analysis between *C. japonica* and *C. obtusa* are shown in Table 4. From the results using the linear discriminant function, the percentage of correct *C. japonica* discrimination was 100% and that for *C. obtusa* discrimination was 95.5%. This result indicates that stand attributes of each species do not influence the distinction between *C. japonica* and *C. obtusa*. This result confirms that it was possible to correctly distinguish between *C. japonica* and *C. obtusa* objects using their corresponding spectral information. Coefficients corresponding to the twelve variables and the constants in the linear discriminant function are shown in Table 5. Values obtained from the substitution of the average and standard deviation of panchromatic data, four bands of multispectral data and NDVI in the objects, which include sample plots, into the linear discriminant function using the coefficients and constant in Table 5 are shown in Table 6. In Table 6, plots of *C. japonica* indicates negative values except one sample plot of *C. obtusa* and other plots of *C. obtusa* indicate positive values.

In this study, about 80 % of plots were established in stands

Table 4 Discriminant result between *C. japonica* and *C. obtusa* using the linear discriminant function

			Predicted group		Total
			C. japonica	*C. obtusa*	
Original data	Number of plots	*C. japonica*	14	0	14
		C. obtusa	1	21	22
	Rate (%)	*C. japonica*	100.0	.0	100.0
		C. obtusa	4.5	95.5	100.0

Table 5 Coefficients and constant of the linear discriminant function in discriminant analysis between *C. japonica* and *C. obtusa*

NDVI_Average	0.936	Band4_Average	−0.005
NDVI_S. D.	0.939	Band4_S. D.	−0.271
Band1_Average	0.154	panchro_Average	−0.066
Band1_S. D.	0.588	panchro_S.D.	0.141
Band2_Average	0.621	Constant	−181.446
Band2_S. D.	1.198		
Band3_Average	−0.195		
Band3_S. D.	−0.197		

Table 6 Values obtained from the substitution of the average and standard deviation of panchromatic data, four bands of multispectral data and NDVI in the objects, which include sample plots, into the linear discriminant function using the coefficients and constant in Table 5

Plot	Species	Value	Plot	Species	Value
2	*C. japonica*	−1.92	1	*C. obtusa*	0.83
12	*C. japonica*	−1.61	3	*C. obtusa*	3.25
13	*C. japonica*	−2.74	4	*C. obtusa*	0.01
21	*C. japonica*	−1.04	5	*C. obtusa*	2.46
22	*C. japonica*	−1.97	6	*C. obtusa*	2.05
26	*C. japonica*	−1.33	7	*C. obtusa*	1.44
29	*C. japonica*	−1.62	8	*C. obtusa*	0.27
30	*C. japonica*	−2.88	10	*C. obtusa*	0.76
31	*C. japonica*	−1.43	11	*C. obtusa*	2.44
32	*C. japonica*	−1.68	14	*C. obtusa*	2.37
33	*C. japonica*	−1.61	15	*C. obtusa*	−0.88
34	*C. japonica*	−1.61	16	*C. obtusa*	0.07
			17	*C. obtusa*	2.12
			18	*C. obtusa*	1.05
			19	*C. obtusa*	0.40
			20	*C. obtusa*	0.12
			23	*C. obtusa*	2.57
			24	*C. obtusa*	0.97
			25	*C. obtusa*	0.97
			27	*C. obtusa*	0.39
			28	*C. obtusa*	1.62
			35	*C. obtusa*	3.40

Table 7 Test for equality between proportions of area by species obtained from forest register and those obtained from object-oriented classification in a compartment

Compartment	Pearson chi-square	df	Asymptotic significance level
219	2.628	2	0.269
220	0.946	2	0.623
221	0668	2	0.716
225	0.910	2	0.634
227	1.511	2	0.470
229	2.285	2	0.319

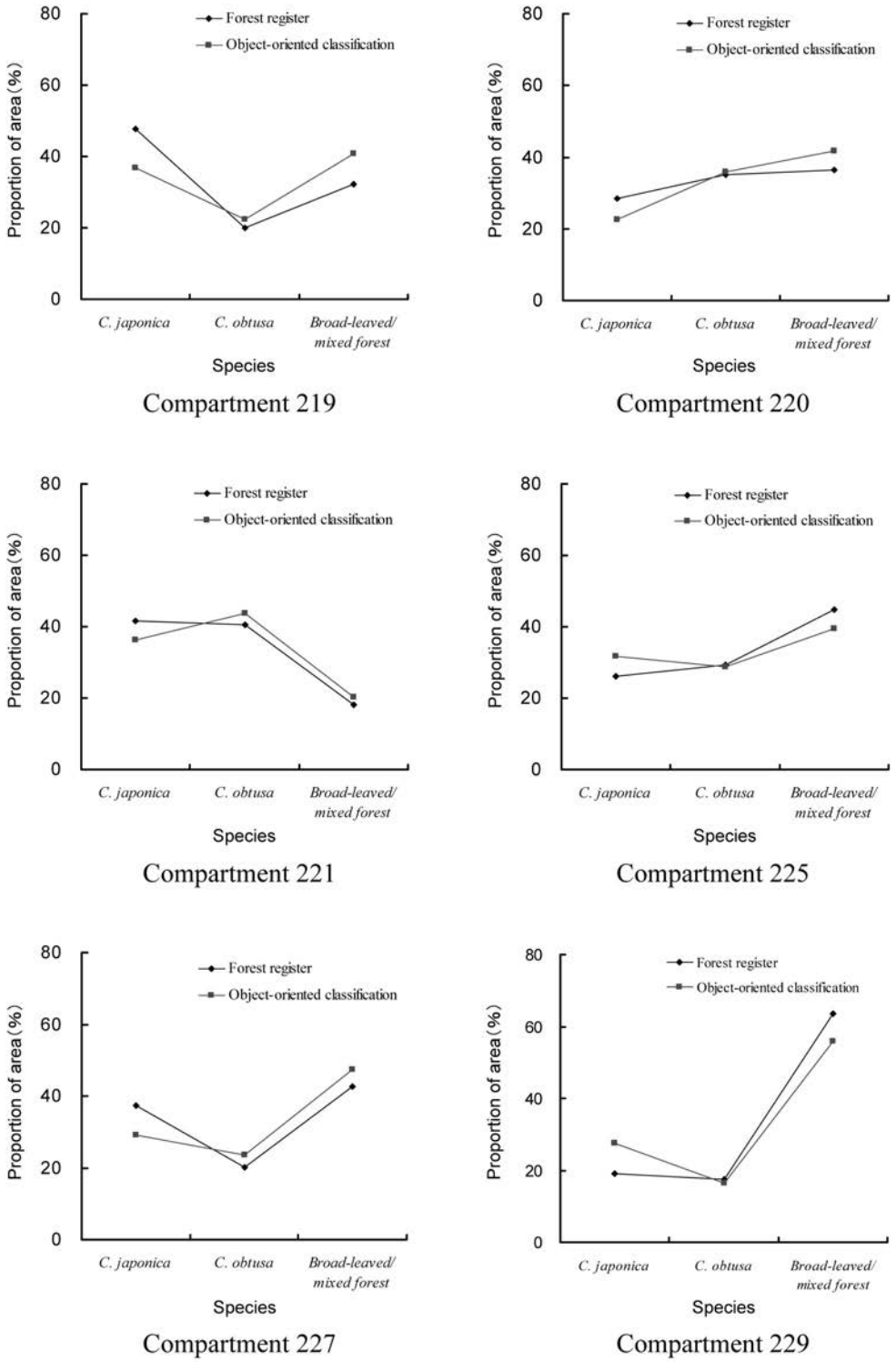

Fig. 7 The results from the comparison between proportions of area by species obtained from the forest register and those obtained from image segmentation of QuickBird data in a compartment

of 21 years to 60 years of age, and this distribution almost corresponds to the stand age distribution of Japanese artificial forests (FORESTRY AGENCY OF JAPAN, 2005). Further investigation is required to distinguish between *C. japonica* and *C. obtusa* stands of 20 years and under of age, where canopy dose not close enough, or those of 60 years of age and over, where some broad-leaved trees invade.

Test for Equality

The results from the comparison between proportions of area by species obtained from the forest register and those obtained from image segmentation and classification of QuickBird data in a compartment are shown in Fig. 7. It is clear that the proportion of area by species obtained from the forest register and that obtained from image segmentation and classification in a compartment are very similar. The results of the test for equality between their proportions are shown in Table 7. The proportion of forest type in each compartment obtained from forest register and that obtained from image segmentation and classification show good agreement, indicating the effectiveness of object-oriented classification in practical use. It is expected that reasonable forest type mapping by object-oriented classification for high-resolution satellite data can be applied to suitable forest management.

CONCLUSIONS

In this study, we investigated the relationship between parameters in image segmentation applied to high-resolution satellite data and generated object size, and we distinguished objects of *C. japonica* and *C. obtusa* by means of discriminant analysis. The findings are summarized below:

1. It is considered that segmentation using 80 to 100 for the scale parameter, with which a stand of the same forest type was divided into three to five objects, is practically applicable to forest type mapping using QuickBird data.
2. Broad-leaved/mixed forests and plantations could be correctly distinguished using the NDVI threshold when we used high-resolution satellite data obtained during the leafless season.
3. Patches of *C. japonica* and *C. obtusa* could be distinguished with the linear discriminant function using the average and standard deviation of QuickBird panchromatic data, four bands of multispectral data and NDVI as independent variables. The percentage of correct results for *C. japonica* discrimination was 100% and that for *C. obtusa* discrimination was 95.5%.
4. As a result of the test for equality between proportions of area by species obtained from the forest register and those obtained from image segmentation of QuickBird data in a compartment, the proportions were in good agreement, indicating the effectiveness of object-oriented classification for practical use.

Object-oriented classification for satellite data is increasingly used in forest type mapping and further progress is expected in determining parameters and evaluating the classification results. High-resolution satellite data is also being applied for estimating stand attributes such as stand density and stand volume in *C. japonica* and *C. obtusa* plantations (HIRATA, 2008; HIRATA *et al.*, 2009), and the integrated use of spatial information obtained from object-oriented classification and stand attributes estimated from panchromatic data analysis will be required.

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Article

Assessment of Forest Covers Change in Tropical Moist Deciduous Forest in Thakurgaon, Bangladesh Using ALOS Data

Sourovi Zaman* and Masato Katoh*

ABSTRACT

The purpose of this study was to outline the present pattern of forest cover and change in Thakurgaon, northern Bangladesh. Forest cover changes were identified and approximately delineated by remote sensing. Remote sensing technologies are used to monitor forests in many parts of the world. The availability of extensive and timely imagery from various satellite sensors can aid in identifying forest area and the rates and patterns of deforestation. We conducted a comprehensive assessment of forest cover changes in Thakurgaon from 2006 to 2008 using imagery from the Advanced Land-Observing Satellite (ALOS). Bangladesh is poor in forest resources, with approximately 14% forest cover in the country as a whole and only about 3% cover in the Thakurgaon area. Rapid population expansion has resulted in increased wood consumption and resource overexploitation that have degraded forest reserves. Near major population centers, large areas have been rapidly converted from forested to non-forested land. The most evident cause of forest loss is conversion of forest to agriculture, for both food and cash crop plantations. By analysis of ALOS imagery, we could clearly identify changes. The results can help foresters identify endangered areas and prioritize management. We found marked increases in forest area in places protected by local governments or private forest owners. Some cultivable land areas were converted into forest and open forest land, although these results may have been affected by cloud cover in the satellite imagery.

Keywords: forest cover, remote sensing, deforestation

INTRODUCTION

Vegetation and forest cover are indicators of environmental quality. Methods of classifying forest cover have progressed in recent years. At present, change detection and mapping are important for identifying areas where improper management has led to deforestation, which could result in further negative impacts such as soil erosion and climate change. Change detection refers to identifying and analyzing the differences in an object or phenomenon by monitoring it at different times (SINGH, 1989; MOUAT *et al.*, 1993). Satellite data have become the major data source for diverse applications including studies of forest cover change. Satellite sensors can collect data over large areas in a timely fashion. The data are accurate, show current conditions, and have flexible applications and digital data acquisition characteristics. A wide range of applications can benefit from studying the change process over a specified area at different times. Recent studies have applied change analysis to various topics including land use, forest cover change dynamics, monitoring of agricultural production, and deforestation (ANWAR, 2002). Information about forest or land cover change is necessary to update land cover maps and for effective resource management and planning for sustainable development (ALPHAN, 2003; MUTTITANON *et al.*, 2005). Furthermore, timely and reliable land and forest cover data may facilitate the formation of integrated resource management policies. However, although detailed, updated information is available in most developed countries, the lack of geospatial databases persists in many developing countries and may hinder proper development planning.

Bangladesh is a developing country experiencing high population growth as well as extreme poverty and unemploy-

Corresponding author: Sourovi Zaman
E-mail: souroviz@yahoo.com.hk
* AFC, Forest Measurement and Planning Laboratory, Forest Science Department, Agriculture Faculty, Shinshu University, 8304, Minami-minowa, Kami-ina, Nagano 399-4598, Japan

ment. This situation has placed great pressure on the country's natural resources, including forests which are threatened by deforestation (BBS, 2006). This situation is most dire in northern regions (AHSAN, 2000) such as Thakurgaon, where people are less educated and more impoverished compared to other areas of the country. The northern regions also experience more droughts. Furthermore, the social system is such that government policy is often disregarded and less emphasis is placed on balanced development (ZAMAN and KATOH, 2009). In Thakurgaon there are very few alternative income sources and a high dependence on the forests. However, inconsistent management and overexploitation of forests have made this important resource unsustainable (IFTEKHAR, 2006).

DAS (1989) suggested that because of population pressure and other socio-cultural factors, most Bangladeshis will not abandon land to allow for forest expansion; rather, their activities regularly harm the forests. Under these conditions, the idea of sustainable forest development and management may seem abstract to local people having limited access to information on land use patterns and change. For sustainable management, it is essential to understand the natural characteristics, distribution, quality, suitability, and limitations of forested areas. This approach requires information on past and present land cover in the area (CHAURASIA *et al.*, 1996). The economic and ecological importance of forests must also be understood (FRANKLIN *et al.*, 2000). Thus the importance of mapping, quantifying and monitoring changes in the physical characteristics of forest cover has been widely recognized as a key element in the study of global change (NEMANI *et al.* 1996). Alongside, the location and rates of forest structural change and the degree to which landscapes respond to these disturbances require extensive investigation (ROGAN *et al.* 2002).

The use of remotely sensed data makes it possible to study changes in forest cover in less time than field measurements, at relatively low cost, and with high accuracy (KACHHWAHA, 1985). Remotely sensed data may be particularly useful in developing countries where recent and reliable spatial information is lacking (DONG *et al.*, 1997). A few studies have examined land use and forest cover changes in Bangladesh (QUADIR *et al.*, 1998; HOSSAIN, 2005; ISLAM *et al.*, 2006), providing information to contribute to sustainable development, many of which have used data from satellite imagery. Considering the need for current information and the urgency presented by rapid deforestation, we focused on the tropical moist deciduous forest of the Thakurgaon district in northern Bangladesh. Using remotely sensed imagery, we investigated forest cover changes during 2006–2008. The results will be helpful for creating a dynamic forest planning and management information system.

MATERIALS AND METHODS

Study Site

The study area in northern Bangladesh was located between 25°57′–25°57′N and 88°15′–88°25′E (Fig. 1), with an area of over 2,497.92 km^2. It was bordered by India to the west and north and is part of the Himalayan plains. The main urban area of the study region is the Thakurgaon district. Forest is estimated to cover only 0.57% of the total area (BBS, 2006). The

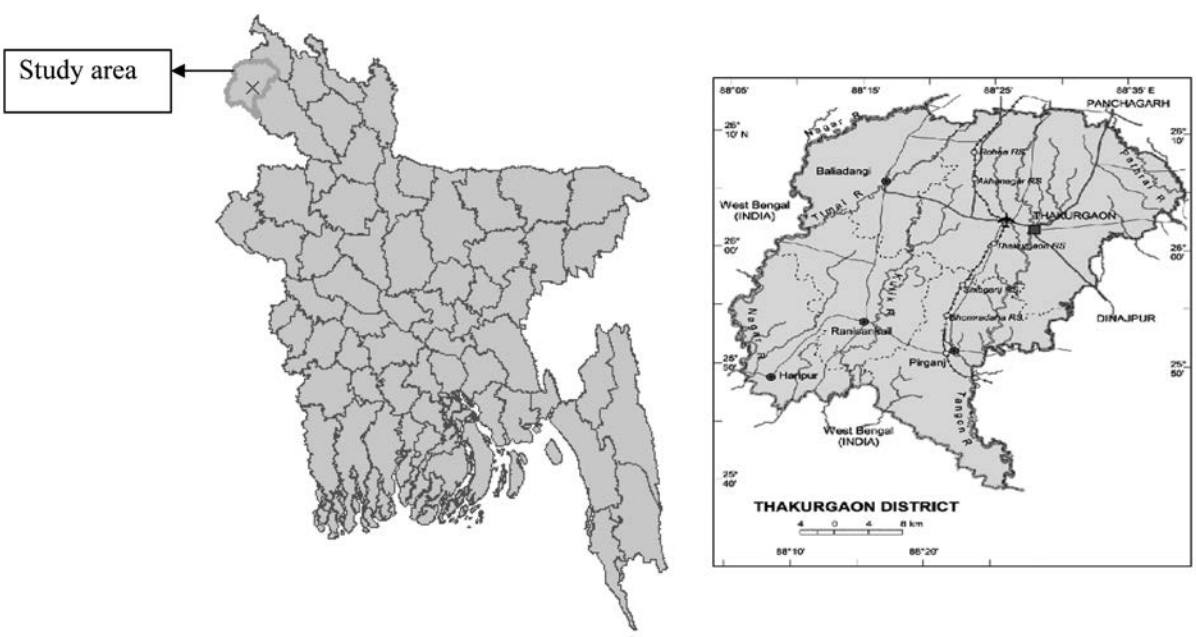

Fig. 1 Map of Bangladesh and Thakurgaon

overall tree crown-covered area (including homestead trees) has been estimated to be only 3% (Dinajpur Forest Division, 2005). The Thakurgaon district is located far from divisional towns and the central part of Bangladesh. The climate is characterized by periods of drought and the rainier monsoon period that usually begins in June and ends in September. Mean annual rainfall ranges from 1,500–1,800 mm (BBS, 2006), and average temperature varies from 26–37℃ in summer and 10–28℃ in winter.

The forest of Thakurgaon is tropical moist deciduous forest. Sal forests are distributed in the relatively drier central and northwestern parts of the country, and multipurpose timber, fruit, and wood tree species are dominant (Feeroz *et al.*, 2000). The study area included the districts of Dhaka, Mymensingh, Tangail, Dinajpur, Rangpur, Rajshahi, and Comilla. The dominant forest species (80–100%) is the commercially profitable Sal tree (Ismail and Miah, 1973). The forest originally supported an indigenous vegetation cover of mixed tropical evergreen forest (Das, 1989); however, almost all of the original forest cover has been removed or substantially altered into secondary forest. Canopy height varies from 10 to 30 m. The upper canopy includes *Shorea robusta*, Tectona sp., *Artocarpus*, and *Hopea odorata*, while the second canopy includes *Syzygium, Gmelina, Dalbargia, and Azadirachta* species. The understory includes Bambusa spp., Alsophila sp., and several ferns and epiphytes (Feeroz *et al.*, 2000).

Materials Used

Satellite imagery

The Advanced Land-Observing Satellite (ALOS) data used in this study were collected on 12 November 2006, 31 December 2007, and 1 April 2008. ALOS was launched by the Japan Aerospace Exploration Agency in January, 2006. The system includes the advanced visible and near-infrared radiometer type 2 (AVNIR-2) sensor with a spatial resolution of 10 × 10 m (Table 1). Images have moderate color contrast for land cover mapping and change detection. Additional tabular data were obtained from the Forest Management Planning Department for the relevant years.

Table 1 Major specifications of AVNIR-2

Observation band	Wave range (micrometers)
Band 1	0.42 to 0.50
Band 2	0.52 to 0.60
Band 3	0.61 to 0.69
Band 4	0.76 to 0.89

Software used

a) GIS (version 9.3.1) was used to omit the cloud cover area for accurate classification. After created the polygons of cloud area linkage to EARDAS IMAGINE and delete the cloud cover portion.
b) MultiSpec Win32 software, a freeware image processing package developed at Purdue University, was used to analyze the multispectral data. The software system classifies land and forest cover from satellite data such as the multispectral observations of ALOS.
b) EARDAS IMAGINE, was used to detect changes from 2006 to 2008. ERDAS IMAGINE provides tools to create, manage, and analyze imagery by simple classification and image interpretation.

Data Analysis

Data gathered by remote sensing can be analyzed to develop land cover classification maps and detect land cover changes (Nemani *et al.*, 1996). To make the data workable, they must need to be transformed to a uniform ground-coordinate system. Here, a universal transverse Mercator (UTM) projection was used. The Geometric projection was converted to WGS84 UTM Zone 54. The center of the study area is located at 88.20E and 25.60N. Because of the high resolution (10×10 m) of ALOS, its images could be used as references to geometrically correct other images.

After inputting data into a computer, rectification was conducted, a geographic projection was re-projected in the shape of a polygonal projection, and the scene was geo-coded. Various information was determined from the IMAGINE attribute table and from the text of Multispec Win. The area obtained from the 2006 ALOS imagery of the study site was compared with those in 2007 and 2008. Different classes of land cover were collected and compared between years. Data analysis was per-

Table 2 Interpretation key for interpretation of ALOS imageries (R:G:B=B4:B3:B2)

Assessment year	Feature	Physical characteristics	Feature color in the images
12th November, 2006	Forest	Tropical moist deciduous forest	Dark red with smooth texture
31st December, 2007	Open forest	Homestead and agroforestry with tree coverage	Red with medium texture, irregular boundary
	Cultivable land	Paddy and other annual or perennial crops	Light green and cyan with smooth texture
1st April, 2008	Water body	River, pond, cannels	Dark green with smooth texture
	Bare land	Fellow land	Whitish

formed with Microsoft Excel 2003.

Interpretation Key

An interpretation key (Table 2) was developed for the study years using the existing forest cover maps compared with the false color composite imagery. Interpretation of the satellite imagery was conducted using Multispec Win 32 with the help of available maps and field visits. For visualization in Red, Green, and Blue (Bands 4, 3 and 2) the open forest appeared as red, forests were in pink red, cultivable land was light green and water was dark green. Table 2 lists the land cover characteristics and interpretation remarks.

RESULTS AND DISCUSSION

To determine land cover changes, classified images belonging to the four main land use classes were re-coded as cultivable land, water body, bare land, open forest, and forest land. Cultivable land denoted land suitable for crops and livestock production, mixed cropping is being practiced with different cropping pattern. Rice and sugarcane are two principal crops. The other crops include potato, wheat, jute etc. Water bodies were the rivers, lakes, ponds, and irrigation lines where areas of open water with no emergent vegetation. Bare land areas which devoid from vegetation, such as sand dunes or exposed soil; this category represents both forest and agriculture fallow. Open forest represented the area where an artificial plantation was being developed by individuals or the government. Forest land was the reserve forest area of the Thakurgaon region, dominating by the tropical moist deciduous tree species. The major species found in this area includes *Shorea robusta, Swietenia macrophylla*, *Neem, Dalbargia* and several multipurpose trees. After the overlay process query, the changes among 2006, 2007, and 2008 were examined. After measuring the area, the areas obtained from IMAGINE were matched with description. The different maps areas were computed from the vector attributes table of IMAGINE. Table 3 gives the spatial distribution of the main land use classes and results of area measurements.

The classified cover maps for 2006, 2007, and 2008 are shown in Fig. 2. The change detection maps for 2006–2007 and 2007–2008 show the changes that occurred between these years (Fig. 3). The maps were prepared from geometrically corrected

Table 3 Showing areas measured from the maps of different land-uses in Thakurgaon

Year	Forest (ha)	Open forest (ha)	Cultivable land (ha)	Water body (ha)	Bare land (ha)
2006	98	1503	2214	153	97
2007	291	2245	1908	297	84
2008	401	2431	1287	412	62

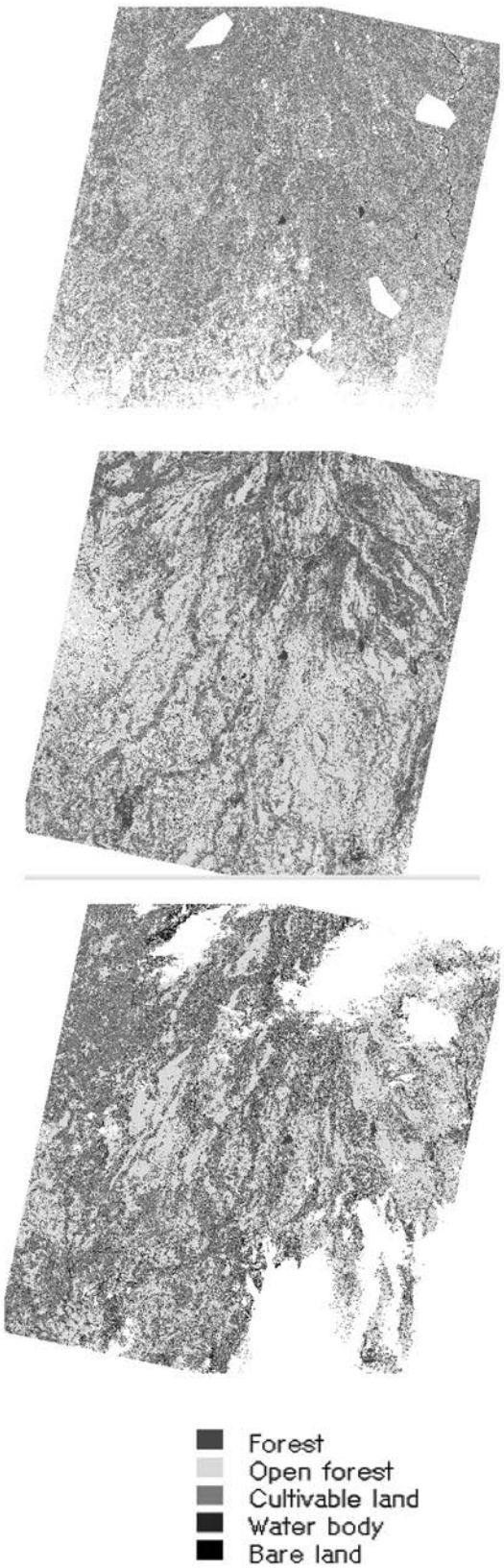

Fig. 2 Classified image of the land-use patterns of Thakurgaon in 2006, 2007 and 2008

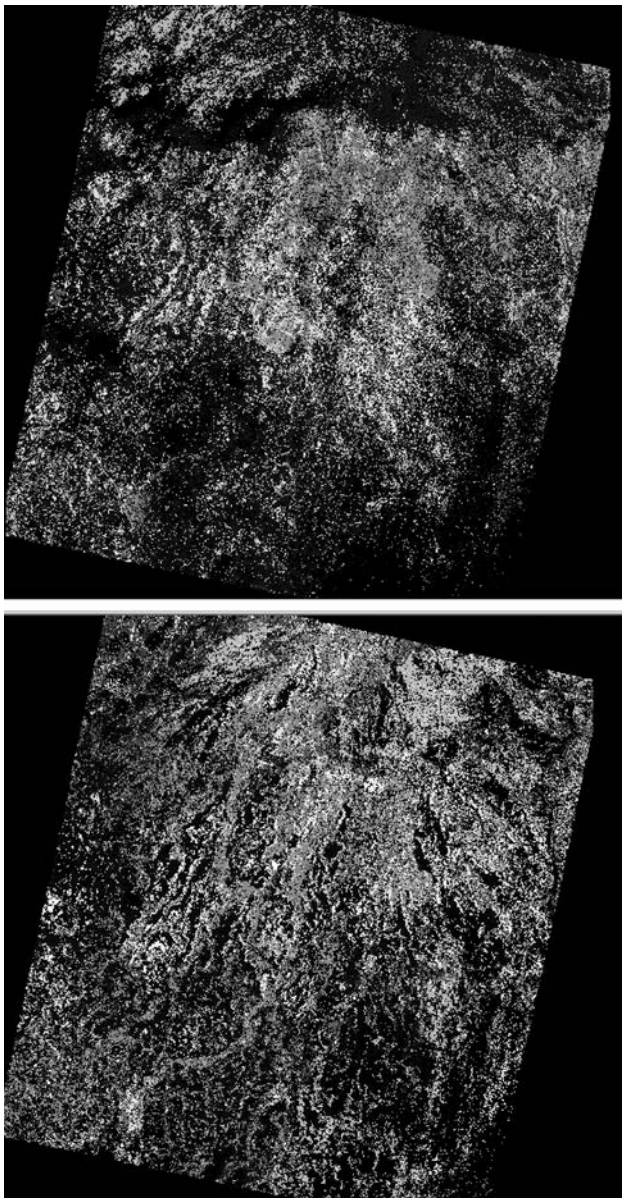

Fig. 3 The trends of change in forest land of Thakurgaon in year 2006-2007 and 2007-2008 using ALOS image

Table 4 Area change rate from 2006 to 2008

Change detection	2006 to 2007		2007 to 2008	
	Area (ha)	Area (%)	Area (ha)	Area (%)
Forest	193	2.75	110	1.57
Open forest	742	10.6	186	2.65
Cultivable land	−306	4.37	−621	8.87
Water body	144	2.05	115	1.64
Bare land	13	0.18	22	0.31

*Minus (−) sign indicate the decreasing of cultivable land; Area (ha) = Prior data of area − post data of area; Area (%) = 100×area of land use class/total area.

images. To manage the polygons in different maps obtained from images of different years, we made a neighboring image. Images recorded at 1-year intervals were compared to determine the direction of change. From 2006 to 2008 the rate of change of land cover was uniform. Forest area, open forest land, water bodies were increased where as cultivated land and bare land decreased.

The major change between the years of 2006 and 2008 was a dramatic increase in the forest area (Fig. 3, Table 3), particularly in 2007. Conversely, the rate decreased gradually in 2008. There was a large increase in open forest land in 2007; however, the open forest area again decreased in 2008 compared to 2007, possibly due to conversion to a forest area of large-crown trees. In 2007 forest area increased by 2.57% and 2008 it was about 1.57% (Table 4). This was the most interesting and hopeful finding of the study. Since 2006, the local Thakurgaon government and private forest owners have given high priority to protecting forest in Thakurgaon, and the government declared some areas as protected parks. Moreover, many people have been engaged in social forestry and agroforestry. The local government of Thakurgaon took a plantation project of road side plantation about 300 km area in 2003 (Dinajpur Forest Department, 2005). The images also showed an increase in water cover, including a number of rainwater collection structures (talais), drainage canals, tube wells, and guzzlers that the Forest and Agricultural Extension Department had constructed to provide water to newly planted forest and open forest land during dry periods. In Thakurgaon major change was happened to the cultivable land area which was gradually decreased from 2006 to 2008 (Table 4). Cultivable land was converted into water body, forest and open forest land. However, there is no or little hope for the expansion of agricultural land in Thakurgaon (heavily populated area) of Bangladesh because almost all land has already been converted into agricultural land. The only possibility left in the region is to intensify agriculture. Multiple and rotational cropping, homegarden agroforestry are among the example of such practice. With the increase of population the pressure on the remaining luxuriant highly rising tree forest is ever increasing and creates effect on the vegetative land. Additionally, bare areas also decreased by this time. Table 4 and Fig. 3 summarize the area change rates and direction of change in the study area.

The most dramatic and indisputable areas of change were found in the open forest and agricultural land, some inland areas showed evidence of change as well. For example, in Thakurgaon, roadside plantation and tree planting in the crop field was commonly practiced by the farmers. Most of this gain was found in areas where new land formed through deposition has become vegetated. This study suggests that forest and open land is being found which the result of sustainable management practice is over the long term, under various protections from forest reserves, national parks, and international designations, agroforestry practice, the forest area seems

Table 5 Confusion matrix for classification accuracy over 3 years in Thakurgaon

(1) 2006

Training class	Volume class					Others	Total	**User's accuracy**
	F	OF	C	W	B			
Forest (F)	**16,150**	812	72	10	0	36	17,080	94.6%
Open forest (OF)	791	**4,311**	766	70	1	42	5,981	72.0%
Cultivable land (C)	0	247	**3,724**	7	0	37	4,015	92.8%
Water-body (W)	0	151	214	**3,046**	0	28	3,439	88.6%
Bare land (B)	0	1	0	0	**1,224**	67	1,292	94.7%
Total	17,141	5,259	4,776	3,133	1,225	273	31,807	
Producer's accuracy	95%	82%	78%	97%	100%			**90** %

Kappa Statistic = **82.6%**. Kappa Variance = 0.000007.

(2) 2007

Training class	Volume class					Others	Total	**User's accuracy**
	F	OF	C	W	B			
Forest (F)	**44,078**	3,202	282	31	0	188	47,781	92.3%
Open forest (OF)	10,516	**46,353**	1,436	85	1	1,719	60,110	77.1%
Cultivable land (C)	0	71	**33,766**	41	128	1,119	35,125	96.1%
Water-body (W)	0	4	12	**2,165**	0	39	2,220	97.5%
Bare land (B)	0	1	0	0	**741**	14	756	98.0%
Total	54,594	49,631	35,496	2,322	870	3,079	145,992	
Producer's accuracy	81%	93%	95%	93%	85%			**89** %

Kappa Statistic = **87.7%**. Kappa Variance = 0.000003.

(3) 2008

Training class	Volume class					Others	Total	**User's accuracy**
	F	OF	C	W	B			
Forest (F)	**16,183**	132	206	81	85	914	17,601	91.9%
Open forest (OF)	132	**17,635**	2	18	11	301	18,099	97.4%
Cultivable land (C)	57	0	**2,422**	208	14	85	2,786	86.9%
Water-body (W)	0	0	269	**5,713**	365	53	6,400	89.3%
Bare land (B)	0	0	3	66	**1,454**	39		
Total	16,372	17,767	2,902	6,086	1,929	1,392	16,372	
Producer's accuracy	98.8%	99.3%	83.5%	93.9%	75.4%			**90** %

Kappa Statistic = **90%.** Kappa Variance = 0.000003.

to be holding relatively stable.

The miss-classification might have occurred between the barren land and the agricultural land due to the seasonality of cropping systems. A typically harvested field might be classified as barren land. Water, due to the mixed pixel effects might have overestimated in some cases. The extent of marshes differs with the season as governed by varying water regime of the area. Moreover, small changes less than 10×10 m pixels were not detected from this study as this was the minimum mapping unit used. This is expected to minimize the errors arising from miss-registration of satellite imageries. Accuracy assessment is very important for understanding and applying the results. We obtained ground-truth data from forest maps and tabular data. Remote sensing-based classifications with accuracy of 80% or above are considered to be accurate and reliable (SWAN and DAVIS, 1978). Three confusion matrices were created to compute overall accuracy, users' accuracy, producers' accuracy, and kappa statistic. The kappa statistics for the

year 2006, for example, indicates that this classification system produce a map on which 82% more pixels were classified correctly than would be expected by random assignment. This means that for this classification, 85% was correct of the time. The classification accuracy ratios for all classes in 2006, 2007, and 2008 were 82.6%, 87.7%, and 90%, respectively (Table 5).

CONCLUSION

Satellite-based remote sensors can obtain accurate data over vast areas, and various software packages facilitate land cover classification and change assessment. This approach enables detection of spatial and temporal changes over time. In this study, we used multi-temporal ALOS images to detect changes in forest cover over 3 years in Thakurgaon, northern part of Bangladesh.

This technique is useful for studying land use in a developing country such as Bangladesh where data and monitoring are lacking. Remote sensing applications have been used for a few decades, but some limitations still exist and require the immediate attention of experts and the government. For example, in developing the supervised classification in this study, we faced problems with poor records of forest resources. Considering this, we suggest the following recommendations for relevant authorities in the study area:

- Forest cover monitoring is needed, as is the need to warn local officials of changes in forest cover.
- There is an urgent need to develop an automated land cover classification method for use in a remote sensing-based monitoring system.
- Maps must be well organized and accurately represent features and their location and distribution.
- Data should be organized by class, with "context-wise" area given.
- Most importantly, further observations are needed.

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Article

Estimation of Tree Density in the Juniper Forest of North-East Iran by ALOS Data

Hadi Fadaei[*1], Tetsuro Sakai[*1], Tetsuhiko Yoshimura[*2] and Moriya Kazuyuki[*1]

ABSTRACT

High resolution satellite images of forests have a key role to play in natural resource management. We describe and evaluate a new analysis technique for; 1- Identification of the juniper's tree crown 2- Estimating juniper forest density by counting trees per hectare, 3- Estimating vegetation indices. In this paper, we introduce a new means of analysis for counting trees, calculation of the vegetation index (VI) and comparison with tree numbers per hectare. Results showed linear regression models between the normalized difference vegetation index (NDVI), the soil adjusted vegetation index (SAVI), the optimized soil-adjusted vegetation index (OSAVI) and number of trees per hectare R^2=0.79, 0.79, 0.87, CV%=19.22, 19.27, 19.22 respectively. In addition, the linear regression of counting trees with the new analysis technique by TreeVaW software and trees measured by ALOS data (Avnir-2 and Prism) R^2=0.72 will be demonstrated. In this study, we have found a useful tool for counting trees in arid and semi-arid regions, thus enabling estimation of biomass and better decision making for natural resource managers in fields of environmental benefit.

Keywords: tree density, *Juniperus polycarpus*, NDVI, SAVI, OSAVI

INTRODUCTION

Juniperus polycarpus is a subspecies *J. excelsa*, which Iranians know as the Persian juniper located in the northeast of Iran. This forest is evergreen or populated by conifers, which is a widespread low-density forest. This species grows within an elevation range of 1,500 meters and 2,000 meters above sea level and belongs to the biggest vegetation zone of five zones in Iran called Irano-Touranian, an area of about 3,452,775 ha. Forests in arid and semi-arid areas are typically scattered with small trees. In recent years, most field studies of forests have concentrated on forest change by using satellite imagery over a period of time, providing mapped results of forest changes seen using Landsat imagery and vegetation cover by Moderate Resolution Imaging Spectrometer (MODIS) data. In recent studies of the arid and semi-arid forest in Iran, tree density has been estimated by forest fieldwork employing various methods, most recently by combining sampling plot and line methods as an inventory method (Transect-Plot) based on the Universal Transverse Mercator (UTM) grid with an admissible relative error 20%. For this process, topographical maps with adequate scale were initially prepared, and then the topographical maps were matched with the UTM grid. An inventory of a specified area of the topographical map was made, gathering data by means of forest fieldwork using a combination of sampling plot and line (Transect-Plot). Before carrying out a total inventory, a primary sampling plot and line (Transect-Plot) inventory must be carried out. A relative error of less than 20% in the primary sampling plot and line (Transect-Plot) must be achieved, in order for data to be used in a final inventory. *Juniperus polycarpus* is most important in these regions for its environmental effect especially in relation to biomass. For this reason, this species and estimation of its population per hectare must be identified. In recent years in these regions, an inventory of trees has been pursued by time-consuming and expensive fieldwork

Corresponding author: Hadi Fadaei
E-mail: fadaei@bre.soc.i.kyoto-u.ac.jp
[*1]Department of Social Informatics, Graduate School of Informatics, Kyoto University, Kyoto 606-8501 Japan
[*2]Educations and Research Center for Biological Resources, Faculty of Life and Environmental Science, Shimane University, Matsue, Shimane 690-8504 Japan

(transport, helpers, tools, measurement devices), then forest data collection with a sampling relative error of 20% or less is needed. In this study, we hypothesize that counting trees by our new analysis technique using TreeVaW software (which has been used to estimate forest tree density at a relatively low cost and with little time consumption), can be a useful tool for counting trees in arid and semi-arid regions. In this study, our first objective is (i) using Advanced Land Observing Satellite (ALOS) data (Avnir-2 and Prism) to identify the juniper tree, (ii) estimation of tree density by new analysis technique for counting trees per hectare, (iii) comparing new analysis techniques using TreeVaW (Tree Variable Window) software and trees measured in the ALOS imagery, and (iv) estimation of vegetation indices. The inventory obtained useful information such as estimation of the canopy cover and major estimators containing the number of trees in the forest of *Juniperus polycarpus*, reducing costs and time taken (particularly significant in arid and semi-arid environments).

Although essential resources for millions of rural people in fewer developing countries, these forests are unchecked and under-inventoried, leading to poor predications of future trends in these forests. There is, therefore, a clear need for better inventory data generated by relatively low cost inventory techniques (GAUTAM *et al.*, 2004; FAO, 2006). In developed countries, inventories are still obtained by mapping forest stands and their content by the interpretation of medium scale aerial photographs backed by field assessments and plot measurements and accomplished by expensive and time-consuming endeavors (GOUGEON *et al.*, 2006). Open forests have special features that provide excellent opportunities for remote sensing-based forest inventory. When a strong relationship exists between forest attributes and the features extracted from remote sensing (RS), these forest attributes can be estimated in a cost-effective way from RS imagery using regression, modelling techniques (OZDEMIR, 2008). A new analysis technique and advances in remote sensing would help obtain detailed measurements useful for sustainable forestry. The combination of new technology for remote sensing and new techniques for data analysis are likely to narrow the gap between users' needs and producers' products. OZDEMIR (2008) has found a strong relationship between field-measured stem volume and tree attributes, including tree crown area and tree shadow area in a sparse Crimean juniper (*Juniperus excelsa* M. BIEB.) forest in southwestern Turkey. Despite recent technological progress in remote sensing applicability and accuracy, little is known about vegetation properties of arid and semi-arid lands other than just the normalized difference vegetation index (NDVI) reflection of the vegetation or soil moisture. In other words, most studies examine the reflection of averaged areas containing trees rather than trees individually. Though the NDVI is a good index of general vegetation properties, it does not provide insights about possible demographic trends in tree populations such as number of individuals, ageing, mortality, spacing, etc (MOUSTAKAS *et al.*, 2009). MOUSTAKAS *et al.* (2009) has found a strong relationship between the number of trees and the canopy area (m^2).

A review of some other research reveals various methods employed for delineation of trees using high-resolution imagery. *Local minimum filtering*; developed the local minimum (L-Min) filtering to detect the darkest pixel with a low value between two neighboring crowns, and utilized the forest area only after discriminating the forest and non-forest using automated or semi-automated classification techniques in a preprocessing step (GOUGEON, 1995). The *local maximum algorithm (LM)* method presented is primarily low-level image processing to segment significant tree crown using image smoothing (BLAZQUEZ, 1989). The purpose of this technique is to round off the contour of each individual tree crown and merge different contour parts that are close to each other, and then applying an edge detection step for a continuous tree crown. Other techniques used are convex curvature and primal sketching of images to discern an individual tree crown. *Tree identification and delineation algorithm (TIDA)*; this method was presented as part of research undertaken as a component of a Ph.D. program at the University of Melbourne (CULVENOR, 2002). This algorithm is based on several criteria; 1- Identification of local maxima throughout the image, 2- Identification of local minima throughout the image, 3- Clustering of crown pixels. *Template matching-based*; this method was introduced and includes a model generation and template - matching (POLLOCK, 1996). A series of models are built to characterize what a tree looks like at different locations in an image by taking into consideration both a tree's geometric and radiometric properties. *Segment boundaries and treetop locations*; This algorithm can be divided into two stages. The first stage utilizes an edge-detection method to obtain initial tree-crown boundaries. The second stage can be separated into two main parts: treetop marker selection and marker-controlled watershed segmentation introduced (WANG *et al.*, 2004). *Watershed segmentation*; VINCENT and SOLUE (1991) introduced this algorithm. With a simple definition, watershed lines are the divide lines of the domains of attraction of drops of water or that splits an image into areas, based on the topology of the image, also we can express process of partitioning a digital image into multiple segments (sets of pixels). Intuitively, for application to image analysis, the watershed lines represent the location of pixels which best separate the dark objects (regional minima), in terms of grey level difference (contrast). *High-pass filtering*; (WALSWORTH *et al.*, 1999) tried to delineate the tree crowns using a high-pass filter. To isolate the crown apex, properties of the original image were enhanced. To locate the crown boundary, an inverted image was generated by substituting the pixel with the lowest value by 255 and the pixel with the highest value by 0. The resultant image enhanced by filtering depends on the image spatial resolution and the window size too. The pixel size of the image must be smaller than the average crown diameter. *Valley-following algorithm*; developed this algorithm (GOUGEON, 1995), used for isolation of individual crowns in Canadian boreal forests. The method finds crown

boundaries by first following the shaded areas (radiometric valleys between trees, and then refining the boundaries using a rule-based program. KATOH *et al.* (2009) investigate conifer plantation management in Japan using high-resolution airborne data based on an individual tree crown (ITC) approach. They have found errors between the ITC approach using the valley-following method and the field-survey data ranging from 0.3 to 30.2%. This error depended on tree crown size, density, and other factors. GOUGEON *et al.* (2006) investigated ITCs; they used high-resolution panchromatic and multispectral bands Ikonos and applied two algorithms for his research. They found overall accuracy was 67 percent. YANG *et al.* (2007) studied on vegetation index for two experiment fields, they recorded Hyperspectral reflectance (350~2,500 nm) data at two different sites of rice in two experimental fields and then applied twenty-five vegetation indices (VIs). The results showed that green waveband normalized difference vegetation index (NDVIgreen) and transformed chlorophyll absorption in reflectance index (TCARI) / optimized soil-adjusted vegetation index (OSAVI) had the best predictive powers for LAI. FAN *et al.* (2009) estimated the relationship between NDVI and LAI in semi-arid grassland in Inner Mongolia using in-situ measurements. They developed a general linear and general exponential relationship

$$LAI = 0.0897 + 1.424\ NDVI\ (R = 0.79), \quad (1)$$

$$LAI = 0.128\ \exp\ (NDVI\ /\ 0.311)\ (R = 0.77), \quad (2)$$

which can be used for various grazing intensity grasslands and for higher vegetation covered areas (e.g. wetland) in the region.

The aim of this study was (i) Identification of the juniper's tree crown, (ii) Estimation of density of juniper forests by counting trees per hectare, and (iii) Estimation of vegetation indices. Subsequently, to determine simple linear relationships between counting trees and vegetation indices, and introducing a new analysis technique for areas of open forest in the arid and semi-arid regions especially juniper forests in the Irano-Touranian region of Iran using ALOS imagery.

MATERIAL AND METHODS

The Study Area

Juniperus polycarpus is a subspecies *J. excelsa*, which is known as Persian Juniper in Iran, mostly located in the north-east of Iran between latitude 36°86′03″ and 37°47′06″and between longitude 58°39′00″ and 59°17′06″ (Fig. 1). This forest has coniferous evergreen trees, which have a low density. This species grow at an elevation range of 1,500 up to 2,500 meters above sea level; belonged to the biggest vegetation zone of five zones in Iran called the Irano-Touranian zone consisting of an area of about 3,452,775 ha. The study area selected for this research has a pure Juniper species, typically 3-4 m tall, with a 3-5 m crown diameter and the space between each tree being above 3 meters approximately. A 1,600-hectare (3,900×3,900 m) area incorporating 12 sampling plots of 9 ha each (300×300 m) was selected for this research (Fig. 2).

The Image Data

The ALOS imagery was used; this satellite was launched on 24 January 2006 by Japan. ALOS image data acquired on 25 October 2007 was used for the analysis. ALOS uses the Advanced Visible and Near Infrared Radiometer type two (AVNIR-2) sensor, which is a multispectral band. This sensor contains of four bands, band1 [blue, 0.42 - 0.50 μm], band2 [green, 0.52 - 0.60 μm], band3 [red, 0.61 - 0.69 μm] and band4

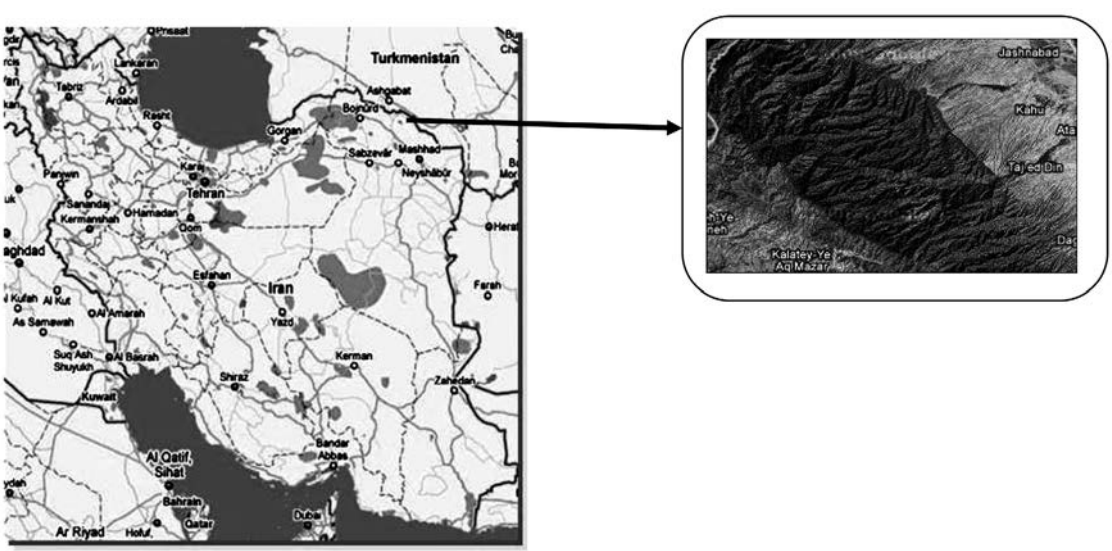

Fig. 1 The study area

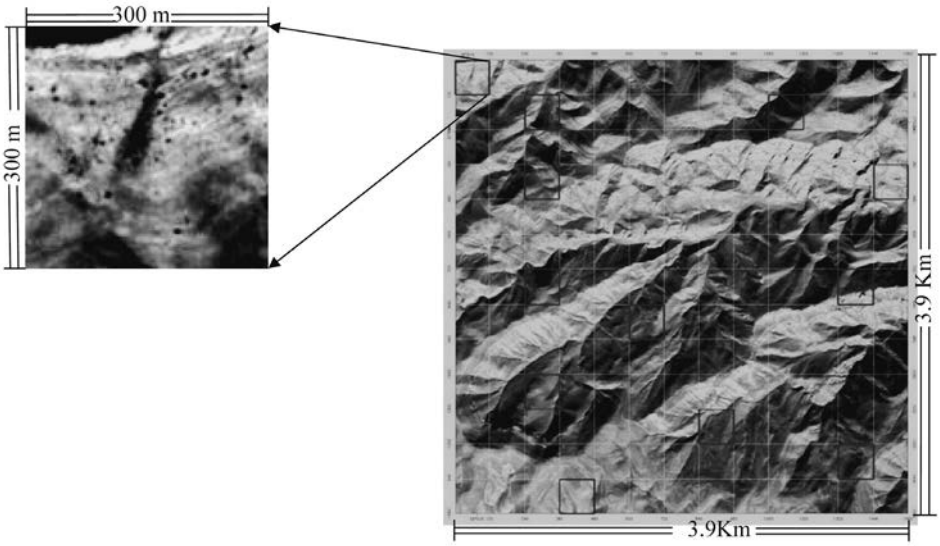

Fig. 2 Position of sample plots

[near infrared, 0.76 - 0.89 μm] respectively. The spatial resolution is 10m at the nadir. In addition, ALOS uses the Panchromatic Remote-Sensing Instrument for Stereo Mapping (PRISM) consisting of these optics; 1- forward, 2- backward 3- nadir. They consist of one band with wavelength 0.52 - 0.77 μm and spatial resolution is 2.5m at the nadir, and swath width 70km at the nadir and 35km at the triplet mode. The field of view is +/-1.5 deg and Quantization (image processing) that can observe the surface of the earth is 8 Bit.

Algorithm Details: Method of Estimating the Tree Density

Estimation of tree density is the key in estimating forest volume. High-resolution imagery (PRISM and Avnir-2) has been used for this method. Image sharpening tools were used to automatically merge a low-resolution color, multi- spectral image using a high-resolution gray scale image (with resampling to the high-resolution pixel size) sharpening technique that uses a mathematical combination of the color image and high resolution data (Bhatnagar *et al.*, 2009). Our algorithm's design was based on the treetop approach. Delineation and identification of Juniper trees (conifers), a regular circular/ellipsoidal/cone-shape is exhibited with a separation tree. Juniper trees are assumed as cone-shaped and the cone apex has a maximum value. Pixels around maximum value have a minimum value denoting the crown of the tree's diameter. TreeVaW software was designed for Lidar data using the treetop algorithm. The results of the local maxima (LM) filtering on the IKONOS data are promising for individual tree identification (Wulder *et al.*, 2004). TreeVaW is an extension of IDL that allows for the extraction of forest stand data using Local Max filtering and variable windows. TreeVaW is a very useful program because it is almost completely automated and it gives foresters the ability to easily analyze large areas of forest remotely. My new analysis technique for counting trees, based on the treetop algorithm, is based on software designed with an LM filter window 3×3 for identification of trees (See Systematic of my new analysis technique is in Fig. 3).

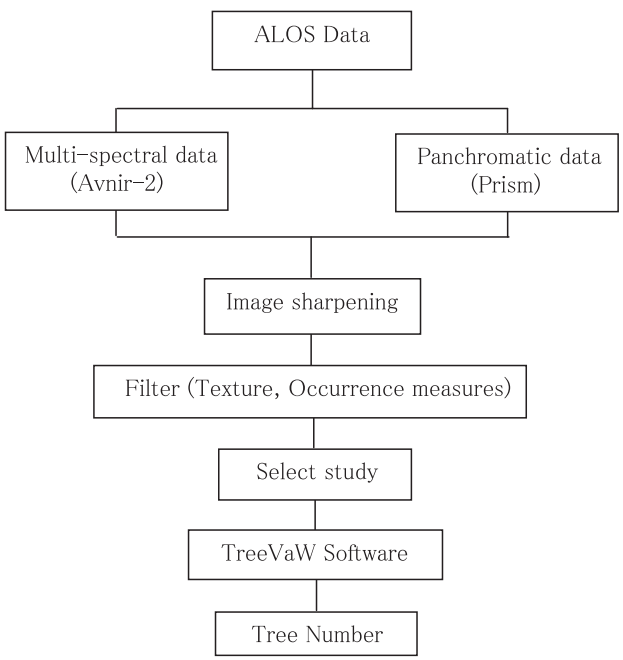

Fig. 3 Diagram of the procedures used for counting tree

Calculation of Vegetation Indices

Explanation of indices

The index used in this study is a ratio-based index called NDVI.

$$NDVI = \frac{NIR - RED}{NIR + RED}, \quad (3)$$

where NIR = near infrared band, RED = red band. Original equation of soil adjusted vegetation index (SAVI) is

$$SAVI = \left[\frac{NIR - RED}{NIR + RED + L}\right](1 + L). \quad (4)$$

$L = 0.5$ in Eq. (4) is optimal adjustment at soil influences.

$$SAVI = 1.5\frac{NIR - RED}{NIR + RED + 0.5}. \quad (5)$$

OSAVI is

$$OSAVI = \frac{NIR - RED}{NIR + RED + 0.16}, \quad (6)$$

$L = 0.16$.

Have been used fusion of images from AVNIR-2 and Prism data, and in fact have used a multispectral band with 2.5 meters resolution to calculate vegetation index (it is necessary to have near infrared and red bands). Since vegetation is green, it absorbs solar energy to form wavelengths of visible light reflectance energy in near infrared. Vegetation indices are variable and relate to the estimation of biomass (RAVI *et al.*, 2008). Subsequently, correlation coefficient linear regressions between vegetation indices and number of trees counted have been calculated from each plot (9 ha).

Data Analysis

Vegetation indices' values have been calculated from a sample plot (9 ha, 14,400 data results equal to the number of total pixels). Subsequently, maximum filtering (3×3) of the 14,400 data results was calculated. Results of maximum filtering (3×3) have achieved 1,600 data results. Subsequently, the frequency of data between ranges of vegetation indices was calculated. Coefficients of linear regression were calculated from results of tree numbers and threshold of filtering data from vegetation indices in the sample plot (9 ha). The computer software used in this study was ENVI, Microsoft Excel, and TreeVaW software.

RESULTS AND DISCUSSION

From A 1,600-hectare (3,900×3,900 m) area 12 sampling plots of 9ha each (300×300 m) was selected that have been calculated relationship between vegetation indices and counting tree. Also for accuracy of TreeVaW, has been calculated relationship between numbers of trees measured from image sharpening and number of trees by TreeVaW software. Results of all the experiments such as NDVI, OSAVI, SAVI and accuracy of TreeVaW are showed in Figs. 4, 5, 6 and 7 respectively, and their assessments including R and CV%. The high R-values of regression models indicate the good relationships between Threshold of data filtering OSAVI and number of tree per hectare. OSAVI is a good index for predicting LAI (YANG *et al.*, 2007). This result of this research accordance with result of

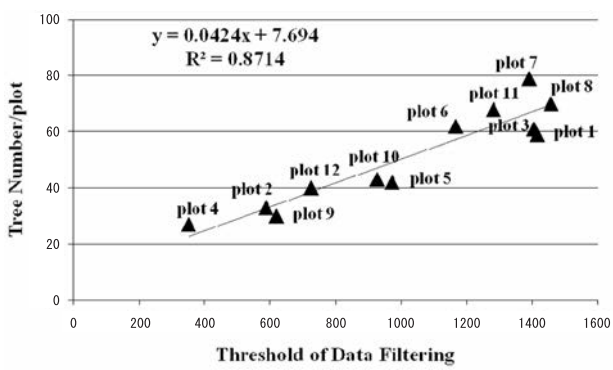

Fig. 5 The relationship between OSAVI (0.1133-0.2008) and number of Tree CV%=19.22

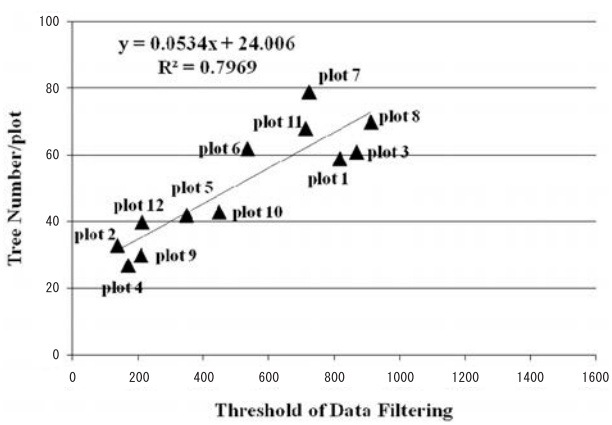

Fig. 4 The relationship between NDVI (0.1216-0.1533) and number of Tree CV%=19.22

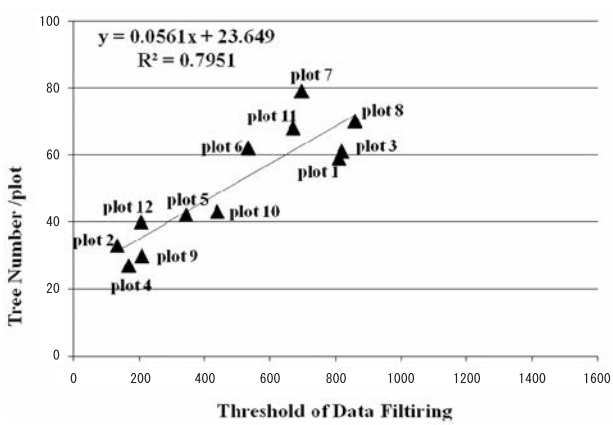

Fig. 6 The relationship between SAVI (0.1965-0.245) and number of Tree, CV%=19.27

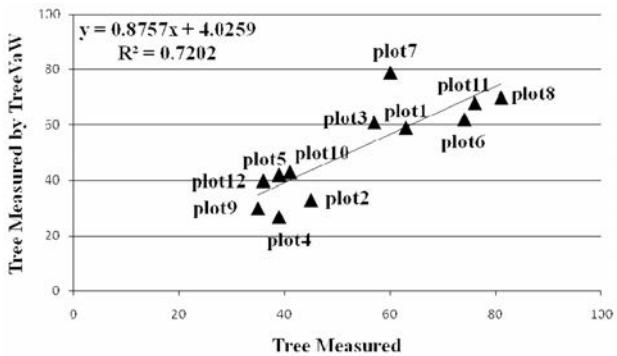

Fig. 7 The relationship between numbers of tree measured and number of tree by TreeVaW software

Estimation of vegetation biophysical parameters by remote sensing using radial basis function neural network was investigated (YANG *et al.*, 2007).

This study was divided into two sections, 1- influences of vegetation indices 2- new analysis technique for counting trees in arid and semi-arid forests. The former is calculated by some ratio between the red (used for photosynthesis, low reflectance from green vegetation) and near infrared (NIR) (high reflectance from green vegetation) wavelengths, while the latter is based on the perpendicular distance to a soil line in two or more band space. The indices used in this study are a ratio-based index called NDVI, SAVI and OSAVI. There is a relationship of positive correlation between vegetation cover and vegetation indices, but this discussion focuses on influences of vegetation indices to distinguish between vegetation. These vegetation indices can be influenced by several non-vegetation factors, such as soil-background, dead biomass and atmospheric conditions (but the latter have mostly been corrected for) (DRISS *et al.*, 2004). There are influences of vegetation indices in the non-vegetation, such as soil background and dry plant material and woody plant (tree). In this study, OSAVI correlated more strongly than SAVI and NDVI (see Figs. 4, 5 and 6). Soil background is a possible factor that was introduced by (HUETE 1988) which adjusting for the slope and origin of the soil-line, the SAVI is the NDVI with the origin shifted by L (= l_1, l_2) : $((NIR + l_1) - (Red + l_2)) / (NIR + l_1) + (Red + l_2))$. The optimal choice of L depends on the vegetation cover, but OSAVI had high ability for distinguishing non-vegetation factors.

In relation to the accuracy of estimating tree numbers in sparsely forested arid and semi-arid regions, using TreeVaW software was effective (see Fig. 7). There is clearly a need for further study on this topic. In addition, some of the methods may need to be changed so that the results are closer to the field data. I hope by employing this method might provide a useful tool for counting trees in arid and semi-arid regions. Moreover, our new analysis technique of counting tree density will be useful for enabling better decision making for natural resource managers in fields of environmental benefit.

CONCLUSIONS

In the present work, vegetation indices on based of LM filter window 3×3 for data filtering was estimated. It will be needed to obtain optimum size of filtering window for vegetation indices in the arid and semi-arid forest. Thresholds or parameters can also be considered as scale modifications when linked directly to object size or indirectly to size through an image property that is size related (DONALD *et al.*, 2005). In future work it need to investigate the relationship between vegetation indices and Juniper trees usage two size algorithms of maximum filtering (3×3) and (5×5) in the sample plots.

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Article

Institutions and Performance of Community Forest Management: Multi-criteria Analysis Framework in a Case of Forest Management in Central Vietnam

Duc Tung Ngo* and Tetsuro Sakai*

ABSTRACT

In the last decades, to cope with the reduction of forest resources and covers, models of community forest management have been considered to apply as a potential system in mountainous areas in Vietnam. There have been many trial models that were applied and are requiring an analysis of the real effects. This article aims at exploring features of the community forest management in terms of forest resources and benefit mechanisms, institutional arrangements and compromises of local people, and clarifying the community's response to this forest management model in Central Vietnam. By applied the multi-criteria analysis approach for the multi-use framework of community forest management, this research revealed that the flexible application in developing benefit sharing regimes based on the forest reserve and stable forest models has been applied as the initiative to give chances of getting benefits from forest resources to local people. Institutional structures as well as roles and responsibilities have also been developed and agreed significantly at the local communities. However, since the allocated forest is low reserves and quality, and inconsiderable capacity of products as to current needs of communities, the participation of those poor communities is still limited. Additionally, lack of detailed planning and orientation after forest allocation has restricted the realization of benefits from forest as well as communities' independence and self-management. Therefore, to solve the realization of benefits that helps to motivate the participation of local people in forest management, it is necessary to consider carefully and use flexibly the integrated analysis framework and solutions. Especially, the attention should be paid to establishment funds for forest protection and development activities within the first five years after forest allocated. At the same time, providing guideline documents and assistance for treating cases violated as well as applying simple sylviculture techniques are also needed.

Keywords: community forest, benefit sharing, organizational structure, interaction pattern, contextual factors

INTRODUCTION

Implementation of multi-sectored economic policies and forestry strategies shifting from management of the State to forestry socialization has been fixed and carried out in early 1990s in Vietnam. Local people's chances of participation as well as their rights and duties in the process of forest resource management and use have been considered and encouraged (Nguyen *et al.* 2008). Many policies such as Law on Forest Protection and Development (1991), Land Law (1993), Decree 02/CP (1994) and 163/CP (1999) on forest land allocation, Decree 01/CP (1995) on land use contraction, etc. have been promulgated in this time. However, legal documents related to land and forest allocation have just acknowledged roles of organizations, individuals, and households.

In early 2000s, forest managed by groups of households and village communities have appeared as formal forms of forest management in Vietnam. Especially, the legal framework on the community forest management (CFM) has been institutionalized from the modified Land Law in 2003, modified Law on Forest Protection and Development in 2004 and modified Civil Law in 2005 (Nguyen *et al.* 2008; Nguyen *et al.* 2006; Nguyen *et al.* 2005). Besides those laws, many polices related to the mechanism of forest management and benefit sharing have been issued in order to support the legal framework, and guide the

Corresponding author: Duc Tung Ngo
E-mail: ngotungduc@gmail.com
* Department of Social Informatics, Graduate School of Informatics, Kyoto University, Yoshida Honmachi, Sakyo-ku, Kyoto 606-8501, Japan

effective implementation of CFM models such as Decision 178/TTg (2001) regarding the regulation of benefit sharing and obligations of forest and forest land receivers, Decision 186/TTg (2006) on the regulation of forest management, Decision 106/TTg (2006) on the guideline of CFM by villages, etc.

It seems that CFM models exist as a target, and take an important role in the systems of forest management in Vietnam. Up to December 2005, village communities were allocated and managed about 173 thousand ha of forest and forestry land (VNDF 2007). After many important policies have been promulgated since 2003, the national department in charge of forestry management has implemented trials on natural forest allocation to local communities in 10 provinces with 40 communes, from 2006 to 2009 (Pham and Le 2009). Its expected results are to develop and check the suitability of the institutional framework of CFM. Thus, many questions such as what characteristics of real forest resources and benefit mechanism are, how the legal framework was institutionalized in the practices of CFM, how the local institutions were agreed and operated in the reality, and what basic issues impacting on the implementing process and results of CFM are raising and need to be addressed.

This study explored the typical features of CFM models in forest resources and mechanisms of benefit sharing, institutional arrangements and compromises of local people to understand the community's response to this forest management model in Central Vietnam. It focused on the local performance and contextual factors that shaped responses into results of forest management. The findings would help to formulate an appropriate model for CFM.

RESEARCH SCOPE AND METHODOLOGY

Selected Study Sites and Characteristics

To understand the issues of CFM, A Luoi district, one of two mountainous districts of Thua Thien Hue province, is selected for field surveys (Fig. 1). This district is 70 km from Hue city in the West. Territory area is 122,954.9 ha in which forestry land is 101,785 ha, land with forest cover is about 96,977 ha, and distributed in 21 communes and towns (ALFPU 2008). Population is 41,717 people in 2007, including various ethnic groups such as Pa Co, Ta Oi, Ka Tu, Pa Hi, etc. (ALSD 2008).

A Luoi district has allocated natural forest to households and village communities since 2003. Up to 2008, 15 households and 13 village communities have been allocated natural forest to manage and protect under different methods and supports (ALFPU 2008). Those trials were carried out under the supports from many organizations such as Forest Protection Department, Extension Training Support Program (ETSP), Stiching Nederlandse Vrywilligers (SNV), United Nations Development Program (UNDP), and Green Corridor Project. Particularly, resource evaluations and plan developments to set up benefit mechanisms following the stable forest model and the forest reserve model have been applied differently in different communes. Thus, Bac Son and Hong Kim communes were selected for in-depth investigations corresponding to each kind of model.

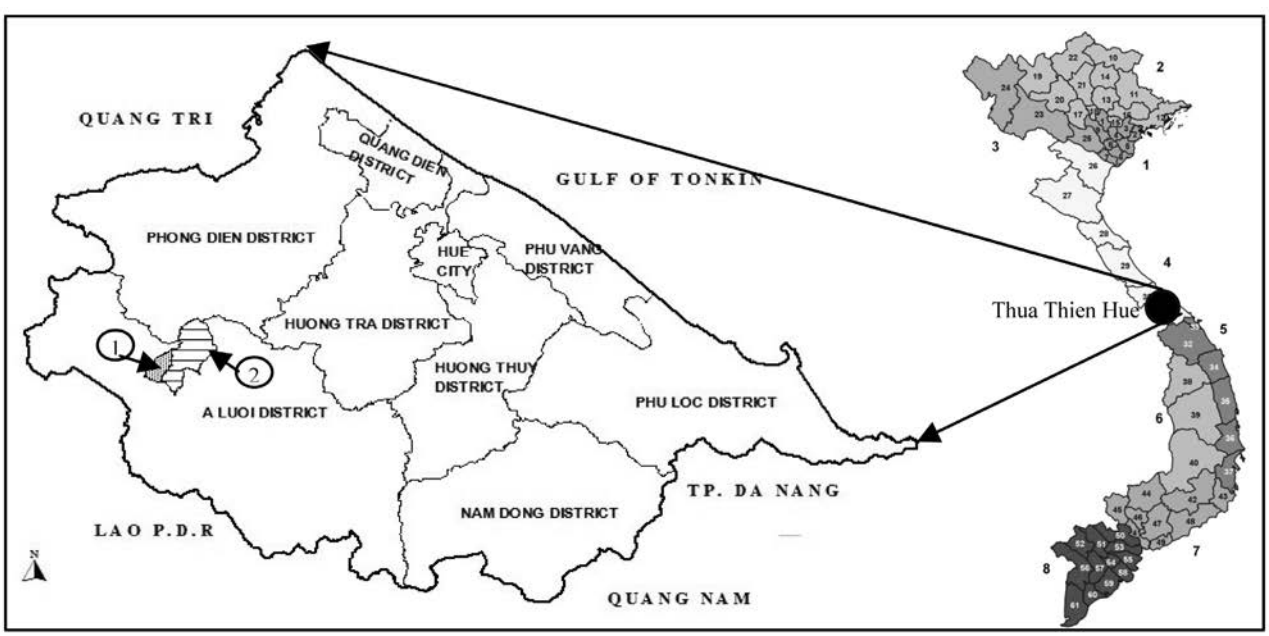

Fig. 1 Research sites in Thua Thien Hue province, Vietnam: Bac Son (1) and Hong Kim (2) communes

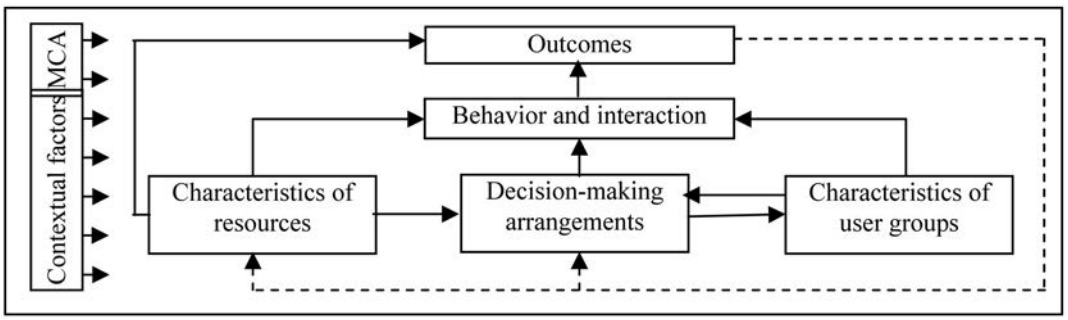

Fig. 2 Multi-use analytical framework of study
Source: Adapted from EDWARDS and STEINS (1999).

Research Methodology

Forest is one of the most important common pool resources and forest under the management model by communities is considered as a kind of collective management models (FAO 1993). To describe sufficiently the management of CFM as a kind of common pool resource management, the use of multi-use framework with considering an analysis of contextual factors is needed. This study, thus, was carried out under the conceptual framework (Fig. 2) that adapted from Edwards and Steins (1999). The main purpose of this framework is to help decision makers to understand the complex situation of CFM delivering from cause-effect relationship between and among aspects. Additionally, this evaluation serves an estimation of results in the future, and gives understanding of the context.

The research used both qualitative and quantitative data with the standard methodology. In each research site, primary data was collected through village meetings, focus group discussions, questionnaire surveys and semi-structured interviews. Moreover, reports and documents synthesized by local authorities and related forestry offices were also colleted to provide important qualitative and quantitative information about the profile of CFM in the research sites. Two stakeholder meetings, ten meetings and focus group discussions with village forest management boards, leaders of communities and local people, and 100 household questionnaire surveys were conducted. The method of stratified random sample selection was used to choose households for the survey.

For outcomes, particularly that of CFM, the qualitative multi-criteria analysis (MCA) approach developed by MEDOZA and PRABHU (2003) was applied. To do that, a meeting with 20 members of village forest management boards was taken place. Firstly, participants were asked to contribute their opinions and suggestions to a basket of Criteria and Indicator[1] (C&I). Then after, they were asked to rank each indicator following a 9-point scale using MCA, in which 1 indicated the lowest value and 9 indicated the highest value. Based on this ranking, average weights and relative weights were calculated using the following formulas:

$$SIC_i = \sum s_j w_j \qquad (1)$$

$$w_j = \frac{a_j}{\Sigma a_j} \qquad (2)$$

where s_j is the score of indicator j, w_j the relative weight of indicator j, SIC_i is the sustainability index of criterion i, and a_j the average weight of indicator j.

The second part of the assessment involves examining each indicator and judging their current condition relative to a 'perceived target or desired condition' by applied the ranking method as mention above. Finally, the composite score at the criterion level was aggregated from the individual conditions and relative weights of the indicators.

RESULTS OF EMPIRICAL SURVEYS AND DISCUSSION

Context of Surveyed Communes

Hong Kim and Bac Son communes are located in the North of A Luoi town and share border with each other. Village communities have been given conditions to receive natural forest to manage since 2006. Particularly in Hong Kim commune, 589.3 ha of natural forest have been allocated to six village communities sine 2007 under technical and financial supports from UNDP (ALFPU 2008). Meanwhile, under the support and assistance from ETSP, natural forest has been allocated to four village communities in Bac Son commune since

[1] Criteria define the essential elements or principles against which sustainability of forest management is judged. Each criterion is defined by quantitative or qualitative indicators, which are measured and monitored regularly to determine the effects of forest management interventions over time. (CASTANEDA 2000)

2006 with the total of 395.5 ha. The general characteristics of natural and socio-conditions of two communes before forest allocated can be summarized as follows.

Hong Kim commune has 4,086 ha of territory area, including 3,789.4 ha of agricultural land, 85.1 ha of non-agricultural land and 211.5 ha of unused land. In agricultural land, forestry land took about 89% of total land, in which natural forest areas were 85.2%, plantation forest areas were 3.8% (HKPC 2005). The commune has 296 households with 1,565 people distributed in 6 villages, in which poor households took 41.6% of total households. Labor forces engaged in agricultural and forestry production were 98% in the total of 701 labors. Forest products took about 20% in the structure of local livelihoods.

Bac Son commune has an area of 1,044.8 ha, including 444.8 ha of natural forest, consisting of 42.6% of the entire commune's land (BSPC 2005). Bald land and unused land occupy 358.4 ha. The commune has 201 households with 1,015 people. People who are in working ages doing agricultural and forestry production occupied 96% of the labor force. This is one of the poor communes of A Luoi district, poor households represented 62%. Forest products took about 15% in the structure of local livelihoods.

Forest Resources and Mechanisms of Timber Benefit Sharing

Village communities in two surveyed communes have affirmed to be subjects who are allocated forest to manage stably for 50 years along with benefit policies based on results of their forest protection and management activities. Officially, benefit sharing mechanisms are mainly based on some issued regulations as mention in the introduction part. However, how these mechanisms are taken place in the reality as comparing with actual forest resources. Thus, these following points are to clarify those issues.

Application of the forest reserve model in Hong Kim commune

In Hong Kim commune, out of 589.3 ha of forest allocated to the village communities, there were about 46% of medium forest (timber volume about 80-150 m^3/ha), 40% of poor forest and 10.2% of restoring forest (timber volume less than 80 m^3/ha). These are shown in Fig. 3. In fact, almost half of allocated forest areas were poor and restoring forest. In the total reserves of 27,450 m^3, reserves with diameter 12-24 cm account for 53.9% and that of greater than 40 cm account for 15.4% (Fig. 4).

The regulation about timber exploitable conditions indicated that in case forest reserves are higher than 110 m^3 of timber per ha then it will be allowed to exploit but only the trees with diameter greater than 35 cm. Therefore, only medium forest can reach to exploitable conditions because their reserve is 123 m^3 of timber per ha at the moment. In fact, there is a little forest reserve satisfied exploitable diameter conditions, about 15-20% (Fig. 4). If based on average growth of forest types, i.e. to restoring forest, annual average growth of timber is 4.2 m^3 per ha and that of medium forest, ranged from 2.8 to 6.3 m^3 per ha up to areas (MARD 2006). In other words, the time for communities to exploit timber from allocated forest is very long. To the type of poor forest, it will take at least 10-15 years to get exploitable reserve conditions and it is even longer to restoring forest, about 15-20 years.

Application of the stable forest model in Bac Son commune

In total area of 395.5 ha that allocated to 4 village communities, the area of medium forest was 126 ha. The remaining areas were poor forest and restoring forest. However, differently from Hong Kim, the evaluation of forest resources to give chances of getting timber benefits was based on the model of stable forest. Results of the survey on sample plots were synthesized as to diameter of 5 cm with colors relevantly from small to big (Figs. 5 and 6). At the same time, the stable forest model corresponding to each forest status has also been established by relevant forestry agencies. This model was used to compare with the model of actual inventory to identify the abundant status of actual forest. If the number of trees corresponding to each diameter in the actual inventory model is

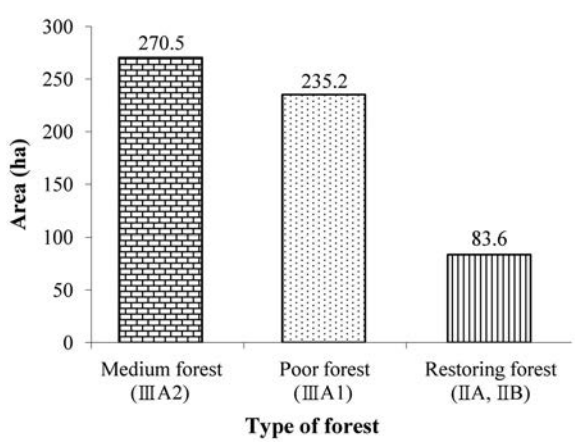

Fig. 3 Area of forest allocated to communities

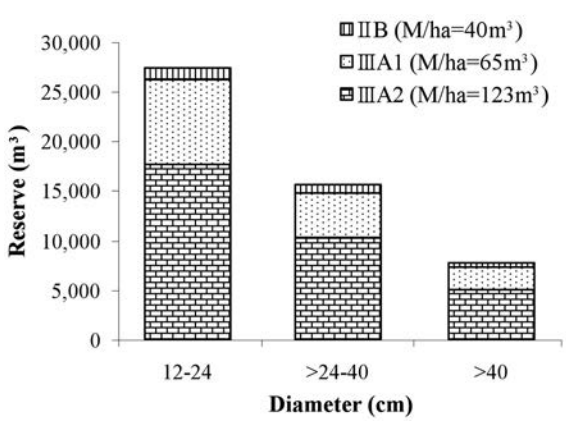

Fig. 4 Reserve and diameter of forest types

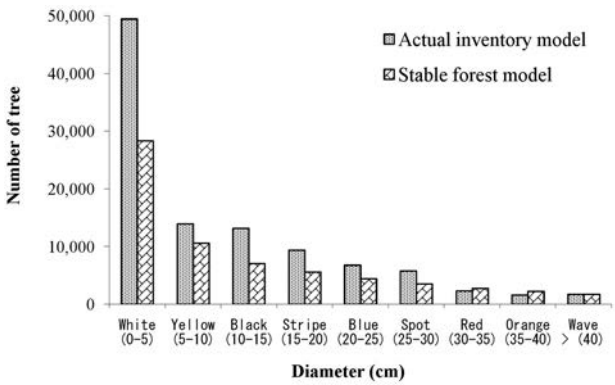

Fig. 5 Number of trees corresponding to each diameter class in the medium forest of Village 1

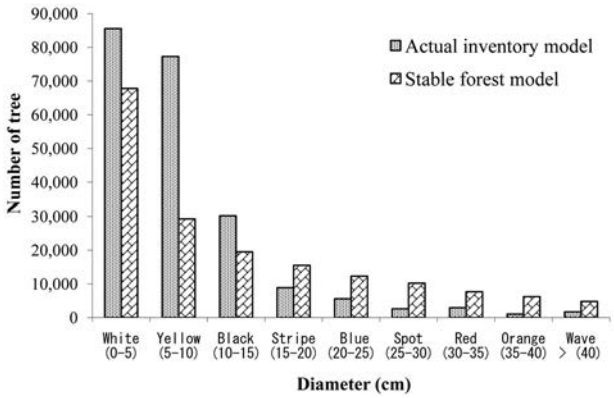

Fig. 6 Number of trees corresponding to each diameter class in the poor forest of Village 2

Table 1 Duties and rights of each level in CFM systems

No.	Category and activity	Level/position in CFM systems		
		Village forest management board (VFMB)	Forest protection team (FPT)	Villagers
I	Duties			
1	Forest Management	- To steer FPT - To follow the change of forest resources - To provide information to relevant levels - To develop, adjust and publicize activities	- To implement guidance of VFMB - To report regularly or unscheduled forest situations and related activities to VFMB	- To join in developing and contributing ideas to contents of activities
2	Forest Protection	- To propagandize and mobilize to enhance local people's awareness - To solve violated cases - To cooperate with functional offices to give training for local people	- To make documents of routes accessing forest and sensitive areas - To patrol regularly or unscheduled for forest protection	- To follow regulations of forest protection - To join in FPT if assigned - To positively prevent or report violations
3	Forest development	- To organize and encourage local people to join activities - To seek and attract investment	- To combine activities of forest taking care and developing during patrol process	- To contribute labors - To plant forest trees by supporting budget or their own budget
II	Rights			
		- To solve illegal violations - To check and propose rights of benefit enjoy, rewarding or punishing - To mobilize labors for forest management, protection, and development	- To prevent violations to forest - To find out, make minutes and to seize and keep exhibit of violated cases	- To contribute ideas to forest protection activities - To monitor the implementation of VFMB and FPT - To join in denouncing and arresting culprits

Source: Village meetings and focus group discussions (2009).

greater than that of the stable forest model, then village communities will be allowed to exploit the surplus number of trees for their needs.

From Figs. 5 and 6, forest allocated to Village 1 and Village 2 was mainly in small diameter classes (5-15 cm). If comparing the number of trees of the actual inventory model with the stable forest model, forest resources in Village 1 could not provide timber with diameter greater than 30 cm within the first five years. The forest in Village 2, especially, could not provide timber with diameter greater than 15 cm. Other sizes of timber, actually, can serve local people's demand if it is necessary.

Organizational Structure of CFM Systems

Under assistance from department of forest protection at

province and district level, department of agricultural extension at district level, local authorities, village headers and villagers, community's conventions and proposals on forest management and protection were established. In these conventions, detail issues related to things that local people have to do, are able to do, are not able to do, and especially, the role and responsibility of village forest management boards (VFMB), forest protection teams (FPT), and villagers were figured out (Table 1).

Structures of participant in the systems are different up to levels, in which there are 3 members in VFMB and 5-10 members in the FPT. The FPT carried out forest patrols regularly based on the allocation from VFMB. Every two weeks, there is one FPT taking charge of forest patrol activities. All local people have responsibilities for and chances of joining this FPT. However, as surveyed, it was known that to villages allocated forest with low reserves, poor forest and far distance, only voluntary and representative groups participated in FPT, such as villages 1-3 at Hong Kim commune and villages 1 and 3 at Bac Son commune, about 50% of total villagers participated in FPT.

To effectively implement those duties and rights, that management system is always put in the cooperation with and support of related stakeholders such as forest protection unit of the district, commune and district authorities, etc. However, initiative roles of this activity still belong to the forest management system of communities while stakeholders will bridge and support if necessary in sensitive circumstances.

Pattern of Interaction and Contextual Factors Influenced Consequences of CFM

Multi-criteria analysis of interaction pattern

Through meeting with VFMB of two communes, criteria and indicators have been identified and given specific value (Table 2). The criteria and indicators that were selected to

Table 2 Estimated weights for indicators and composite score at criteria level for CFM

		Local people's perception			Reality of CFM	
No.		Criteria and Indicators	Average weight	Relative weights	Average scores	Composite score
1		Improvement of awareness and capacity building				5.04
	1.1	Propaganda and mobilization	8.5	0.40	8	
	1.2	Training on forest management and protection	7.2	0.34	2.5	
	1.3	Educating violators within community	5.5	0.26	3.8	
2		Organizational systems				6.47
	2.1	Setting up structure of organization	6.5	0.23	8.6	
	2.2	Assigning role and responsibility	7.8	0.28	7.2	
	2.3	Cooperation among members within the system	8.2	0.29	5.5	
	2.4	Cooperation with related stakeholders	5.4	0.19	4.3	
3		Forest protection patrol activities				5.43
	3.1	Patrol schedule	5.4	0.19	8.3	
	3.2	Implementation of patrol	8.7	0.31	5.5	
	3.3	Number of participants	6.5	0.23	4.3	
	3.4	Identifying route of patrol	7.2	0.26	4.2	
4		Effect of forest protection				5.75
	4.1	Reducing violation cases	8.7	0.40	5.8	
	4.2	Forest fire	5.5	0.25	8.7	
	4.3	Discovering and treating violation cases	7.4	0.34	3.5	
5		Forest care and development				2.72
	5.1	Taking care of forest	5.6	0.26	2.3	
	5.2	Forest plantation	7.4	0.35	4.4	
	5.3	Reforestation	8.2	0.39	1.5	
6		Other required supports from relevant departments				2.53
	6.1	Guideline documents for treating violation cases	6.3	0.22	2.3	
	6.2	Guideline documents of simple sylviculture techniques	5.5	0.20	2.1	
	6.3	Legalization of organization	7.8	0.28	4.5	
	6.4	Establishing funds for forest protection and development	8.6	0.30	1.2	
		Average composite score of all criteria				4.66

analyze the consequences of CFM are diversity including 6 criteria and 21 indicators. Criteria cover integrated aspects such as awareness and capacity building, organizational systems, forest protection patrol activities, effects of forest protection, forest care and development, and other required supports from relevant departments. In each criterion, important indicators were figured out with relative weights to criterion. The propaganda and mobilization, cooperation among members, implementation of forest patrol, establishment of fund for forest protection and development, etc. are examples representing for important indicators that influenced to each criterion. Based on the practice of CFM and desired condition that mention in community's conventions, almost the criteria were around medium levels as compared with the desired condition. The organizational systems and effects of forest protection activities achieved high value. However, criteria 5 and 6 just got around fair conditions to the desired condition. These criteria are very important complements to improve the effects of forest management but it is still not considered yet.

Contextual factors analysis for community's responses

Besides the results shown in Table 2, the contextual analysis corresponding to specific issues will provide and complement more detail to understand the essence of those consequences. As to that, rich pictures in terms of local performance and achieved results are summarized as following notes.

Regarding improvement of awareness and capacity building activities, about 95% of people joining in the survey said that the forest allocation program for communities' management was very much suitable and meaningful. Local people admitted that they were more responsible for and interested in forest management and protection since they became real forest owners. Propaganda to enhance awareness was integrated in village meetings almost every month. However, training activities to improve effectively capacity for forest management were still shortcomings. Only people in VFMB were able to participate in and only in the first steps of the forest allocation process. Therefore, lack of knowledge and inconsistence in application has been happening and are difficult to avoid in reality.

Organizational structures were almost fully implemented at two communes. VFMB and FPT were established with its responsibilities and rights. However, in terms of the implementation of activities, it was about 70% resulted. It was partly because of the lateness in transferring necessary instructing documents to communities from functional offices, such as village communities in Bac Son still have not yet received essential documents. On the other hand, due to the passiveness in researching and learning about legal documents such as in Hong Kim, implementation and treatment of activities are limited. Especially, 100% of people in the survey said that since there was no official decision for FPT, it was very difficult for them to carry out patrol and control activities.

Forest patrol activities as to the regulations is periodically implemented, i.e. at least every two weeks, there will be a FPT patrolling of forest in charge. Moreover, the FPT also needs to make the outline of necessary patrol routes and sensitive areas. The patrol activity was well done in the first stage after forest allocation. However, after that, the distance between times was increased up to two months or even not any time from January to June in 2008 such as village communities in Bac Son commune. As explained by local people, it was because there was no allowance for forest patrol activities and no legal decisions for the operation of FPT. Hence, they were not motivated to fulfill their duties. Moreover, the patrol was only done as to one fixed route but not to develop effective patrol routes so that its effectiveness was limited. Additionally, even though it was mentioned clearly in policies and regulations of community forest management that communities would get benefits from obtained results via activities, there were 90% of participants wishing to get allowance.

Harmful impacts on forest resources have been decreased significantly as compared with before forest allocation program initiated. This effect was about 60% at both communes. However, many cases of violation were still from insiders. Therefore, treatments of those violations as to regulations of forest management and protection have not been fully implemented. Issues of relationship, economic condition and reasonable causes proposed by violators are key reasons for all cases not solved as stipulated.

The forest care and development are also important activities together with forest protection activities. These activities can be happened under various methods: restoration-oriented protection, care of forest, artificial regeneration and forestation. However, due to low economic condition and dependence on resource exploitation of local people, lack of support and assistance from relevant agencies, those activities almost have not been done so far. Moreover, in terms of management, identification of specific features for each forest resource area, as well as particular regulations about the contribution of individuals in communities has not been developed. Therefore, consultancy combining simple forestry techniques is urgent needs apart from needs of support to restore forest.

CONCLUSION AND WAY FORWARDS

This study provided further supports to understand the reality of institutional arrangements and community's response to this CFM model. It revealed that local people really joined in the decision making process since they were allocated natural forest to manage. This has encouraged and motivated local people in responding, deploying and implementing management activities. In addition, local regulations and institutions legalized at the community level with the supports from local forest officers have allowed local people to directly participate in forest management, protection and development activities and to take responsibility in their forest areas. As to this way, communities' confidence and responsibilities have

been improved and their initiative in self-management was also enhanced. However, due to lack of guidance, assistance, and cooperation from related stakeholders after forest allocated to communities, the implementation of local regulations was low enforcement, especially in avoiding and treating violated cases. Therefore, these issues should be considered significantly at least five years since forest were allocated.

It was also found that besides common legal framework and policies of CFM, due to features of pilot models, the evaluation of forest resources to set up benefit sharing mechanisms has been applied differently. Principles based on the forest reserve and stable forest models have been applied relevantly for the mechanism of benefit sharing in Hong Kim and Bac Son communes, respectively. Both the stable forest model and the forest reserve model have different advantages and disadvantages. The stable forest model has initially shown the initiative in creating chances of getting benefits from timber with different sizes directly after receiving forest to communities. Estimation of communities' needs and forest resources providing have also been considered. Meanwhile, the forest reserve model has shown the simplicity in evaluating resources for officers and ease in identifying an amount of timber that communities are allowed to exploit. In both cases, communities are enhanced chances of getting benefits from timber and other kinds of forest products. However, in reality at two research communes, most of forest allocated to communities was low reserves and quality, which limited the participation of local people in managing and protecting forest. Moreover, it limited local people's chances of enjoying benefits, and development potentials of this forest management model. In fact, the biggest challenges are to manage forest sustainably after forest allocation and how to let local people get benefits from the allocated forest in a shortest time. Differences of natural resources among forest areas, poor forest reserves, unclear ecological advantages and long business rotation, etc. are reasons why local people cannot get benefits immediately after being allocated forest any more, especially benefits from timber. Therefore, there should be flexible applications about benefit and investing policies for different communities. Moreover, it is necessary to motivate the establishment of funds for forest protection and management activities of communities. It is because responsibilities and rights should be always together. Especially, to currently difficult situation of communities being allocated forest, it is more urgent.

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Article

Estimating of Timber Resources from Large Diameter and Long Materials Used for Wooden Cultural Buildings

Juri Sato[*1], Satoshi Unno[*2], Naoko Yumoto[*3], Hirokazu Yamamoto[*1] and Toshio Tatsumi[*4]

ABSTRACT

Wooden cultural buildings are a symbol of Japanese culture. It is necessary to secure a supply of large logs to maintain these important cultural buildings in perpetuity. Besides to having a large diameter and length, these logs need to have a high quality of wood. However, it is difficult to secure a permanent supply of such logs. That is because required large diameter and long materials logs are usually not offered at a customary timber-market. Prescribed conditions to maintain important cultural buildings are strict and require using the same building technique as well as using the same tree species of the same tree quality. That imposes a demand for the trees of the same kind, size and wood quality as it is used in existing wooden cultural buildings. Therefore, there is a need to conduct a research on the quantity of the demand and to investigate capability of forests to fulfill such demands. We need to secure a sufficient supply of required trees and to find out a present state of large sized trees. This paper presents our developed technique to estimate a standard size of standing trees which have served to produce a large-sized building material for wooden structures.

We have taken a representative sample from published reports on Japan's cultural buildings built throughout Heian (794-1185) and Kamakura (1185-1333) period. Furthermore, in order to presume the size of saw-wood, we have measured logs at the warehouse and have calculated the width of sapwood. Moreover, in order to calculate the height and the relative taper-curve using a three-order equation, we have measured heights, DBH as well as diameters along the trunks of standing Japanese cypress trees growing at Kiso area of Japan. Finally, we have estimated standard sizes of standing trees which have served to produce a large-sized building material for wooden structures.

Now, we have information on standard sizes of standing trees which have served to produce a large-sized building material for wooden structures. Furthermore, using our developed technique and measuring only the DBH, now we can assess a present state of standing trees being suitable for the maintenance of wooden cultural buildings. The standing trees being the most difficult to obtain were the trees of size used to build the 18 pillars of Nandaimon at Todaiji temple. These pillars have a size of 1 meter in diameter and 19.17 meters in length. We have estimated that the standing trees should have a DBH more than 150 cm to be of use in producing such large sized pillars. Even at Kiso area where a large-sized Japanese cypress trees still can be found, it is extremely difficult to secure a supply of trees having a DBH larger than 150 cm. Hereafter, the present state of large trees should be assessed. Furthermore, a relatively large forest area should be bequeathed for the purpose of securing a permanent supply of large-sized trees having a required good-quality. Our next tasks are to follow up the growth of the prospective trees in forests.

Keywords: wooden cultural buildings, large diameter and long materials, *Chamaecyparis obtusa*, timber resources

Corresponding author: Juri Sato
E-mail: juri09a@nenv.k.u-tokyo.ac.jp
[*1] Graduate School of Frontier Sciences, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8563 Japan
[*2] Nara National Research Institute for Cultural Properties Researcher, 2-9-1 Nijomachi, Nara-Shi, Nara-Prefecture 630-8577 Japan
[*3] Kurashi no Kenchikusha, 2-17-1-418 Sakuragi, Senju, Adachi-ku, Tokyo 120-0045 Japan
[*4] Tatsumiya, Tatsumi Shouten, 5-8-3 Kiba, Koutou-ku, Tokyo 135-0042 Japan

INTRODUCTION

Wooden cultural buildings are the symbols of Japanese culture. As of December 2009, there are 4,566 cultural buildings (Agency for Cultural Affairs, 2009), and about 90 % of them are wooden. The characteristic of the wooden structure is to use the plant material, and it can reproduce continuously. It is necessary to secure a supply of material to maintain wooden structures. The architecture scales of the wooden structures are various; in particular, a large diameter and long material is used for the main parts: the pillar, the beam and the door of large-scale architecture. However, it is difficult to secure a permanent supply of such logs. That is because required large-high-quality logs are usually not offered at a customary timber-market.

According to the consumption quality data of the repairs of the national treasures and the important cultural properties which were built from 1976 to 2000, the tree species with the highest demand is *Chamaecyparis obtusa* followed by *Cryptomeria japonica* and a *Pinus thunbergii* (Shimizu, 2005). Prescribed conditions to maintain important cultural buildings are strict and require using the same building technique as well as using the same tree species of the same tree quality. That imposes a demand for the trees of the same kind, size and wood quality as it is used in existing wooden cultural buildings. Therefore, there is a need to conduct a research on the quantity of the demand and to investigate capability of forests to fulfill such demands.

We need to secure a sufficient supply of required trees and to find out a present state of large sized trees. This paper presents our developed technique to estimate a standard size of standing trees which have served to produce a large-sized building material for wooden structures.

MATERIAL AND METHOD

We have taken a representative sample from published reports on Japan's cultural buildings built throughout Heian (794-1185) and Kamakura (1185-1333) period (Unno, 2008). In this study, the large diameter material defined more than 45cm, and long material defined more than 6 m. In the market, the size isn't generally treated. First, it calculated a necessary raw wood standard from the information on the large diameter and long materials. Next, it estimated the size of standing tree that is necessary to get raw wood.

Estimating of Raw Wood Standard from the Large Diameter and Long Materials

The material assumed that one material takes from one raw wood. In the main structural part at the wooden structure, only the heartwood which is excluded sapwood is used to improve durability and to suppress the distortion of the material. As for the estimation of the heartwood part, it depends on whether the part is the log or the square lumber.

The log used the length of the diameter. The diameter of the square lumber used the length of the diagonal line. The raw wood standard which is necessary to get a material with top end diameter of 45 cm need to add the sapwood width to the heartwood part. The sapwood width used the result of the investigation in the raw wood market in December, 2007. Sapwood width is defined 4.4 cm from the result (Sato et al., 2008).

Estimating of Standing Tree Standard from Raw Wood Standard

About the estimation of standing tree standard from the raw wood standard, it estimated only Japanese cypress with the highest demand for the material of the repair. Our study site was in Kiso area, which is located in Nagano prefecture. The largest amount of large-sized and high-quality cypress trees, aged more than 300 years, is supplied from the Kiso area. In October 2007, we measured the natural 100 Japanese cypress trees. We have made a height-diameter curve (Nagumo and Minowa, 1990) and a relative taper curve (Nagumo and Minowa, 1990). The height-diameter curve is

$$H = 11.49 \times \log(DBH) - 19.21 \quad (R^2 = 0.29), \tag{1}$$

where H is total height of tree and DBH is diameter at breast height of tree. The relative taper curve is

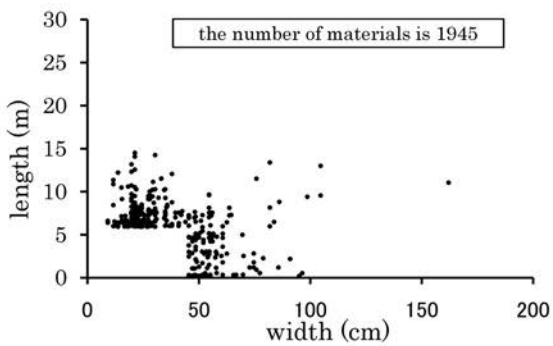
$$y = 2.2892x^3 - 4.0936x^2 + 2.9394x \quad (R^2 = 0.86), \tag{2}$$

where y is relative diameter and x is relative height. These curves are used for the estimation of standing tree standard from the raw wood standard.

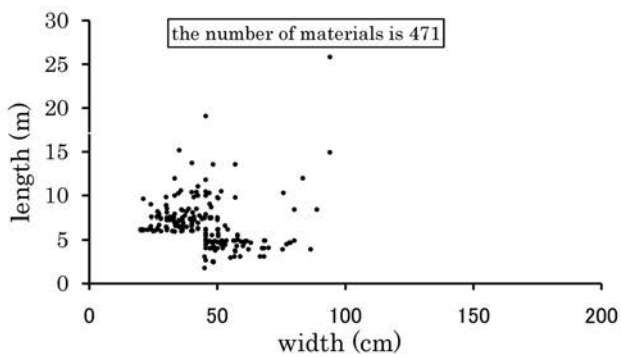
RESULTS

3,955 material sizes of large diameter or long materials were shown according to the types of the buildings; temple, castle and folk house (Fig. 1). Comparing the longest material, temple is 19.2 m, castle is 25.9 m and house is 24.0 m. The reason the material in temple is the longest is because large diameter and long materials are used for the pillar. Also, in house, long materials are needed for the beam. Comparing the largest diameter material, temple is 162.0 cm, castle is 93.9 cm and house is 80.0 cm. In addition, as for the diameter in the temple, about 100 cm diameter materials are used. In contrast, in the castle, about 70 cm materials are used. In the case of folk houses, the size of materials is comparatively fixed; however, big materials are sometimes used.

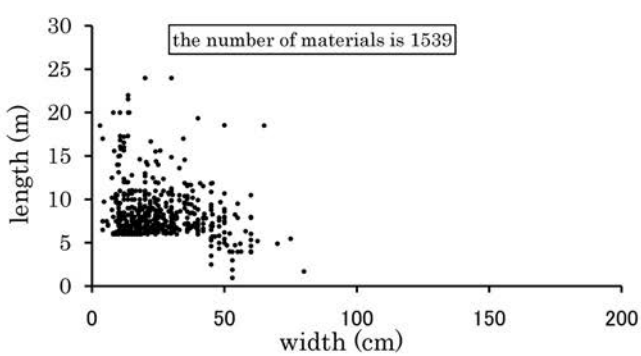
The material volume is about 2,400 m^3 (Fig. 2). Considering the parts are sharpened by a sawing process, the necessary quantity of raw wood to get the volume is about 3,900 m^3, namely, 1.6 times resources of materials. The tree species, which



a. Material size of temples



b. Material size of castles



c. Material size of folk houses

Fig. 1 Material size of large diameter or long materials according to the types of the buildings

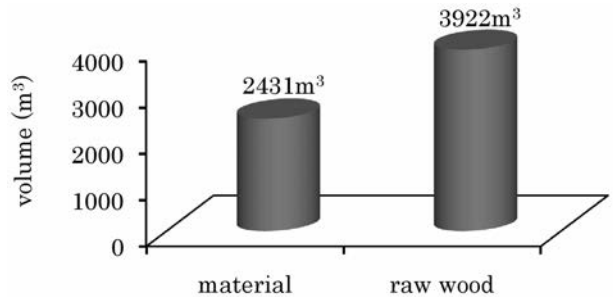


Fig. 2 Comparison of volume between material and raw wood
It was estimated from material volume and raw wood volume.

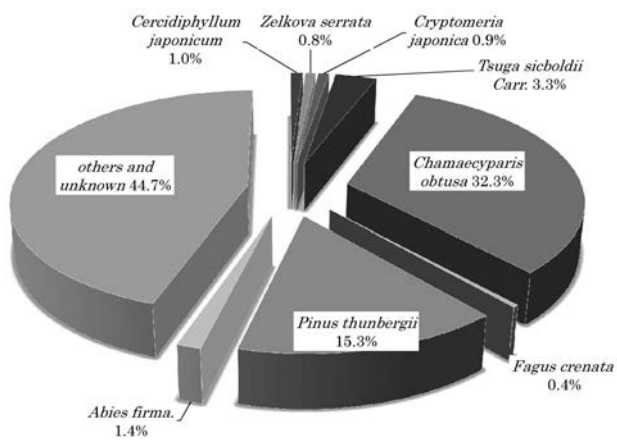


Fig. 3 The graph of tree species is used for large diameter and long materials

are used for the large diameter and long materials are shown (Fig. 3). From the results, *Chamaecyparis obtusa*, *Cryptomeria japonica*, *Pinus thunbergii*, *Tsuga sicboldii* Carr. and *Abies firma* are used in conifers; also, in broadleaf trees, *Cercidiphyllum japonicum*, *Zelkova serrata* and *Fagus crenata* are used.

Based on 137 pieces of raw woods, the raw wood size in each tree species is shown (Table 1). *Chamaecyparis obtusa* and *Pinus thunbergii* are used well. The size of the pine was almost fixed; however, the size of *Chamaecyparis obtusa* was various. In particular, the large diameter and long material of *Chamaecyparis obtusa* was used in the Jodoji-Jododo (Fig. 4) and Nandai-mon at Todaiji-temple (Fig. 5). About elevation of Figs. 4 and 5, the part of large diameter and long materials was shown in Table 2. The standing trees being the most difficult to obtain were the trees of size used to build the 18 pillars of Nandaimon at Todaiji temple (Table 3). These pillars have a size of 1 meter in diameter and 19.17 meters in length. Using the height curve and the relative taper-curve produced by the three-order equation, we have estimated that the standing trees should have a DBH more than 150 cm to be of use in producing such large sized pillars.

DISCUSSION AND CONCLUSION

Now, we have information on standard sizes of standing trees which have served to produce a large-sized building material for wooden structures. Furthermore, using our developed technique and measuring only the DBH, now we can assess a present state of standing trees being suitable for the maintenance of wooden cultural buildings. In the tree species *Cryptomeria japonica* is high demand as for the repairing materials

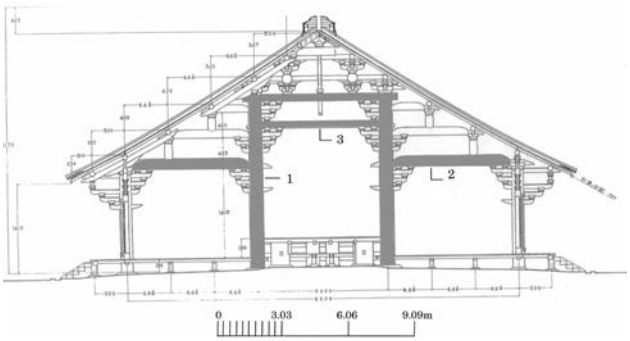
Table 1 Raw wood size for large diameter and long materials in each tree species

spiecies	name	diameter (cm)	length (m)	number of materials
Chamaecyparis obtusa	Jodoji (temple)	71.6	8.2	4
	Jodoji (temple)	64.7	7.6	4
	Jodoji (temple)	64.7	7.0	4
	Jodoji (temple)	64.7	9.6	4
	Jodoji (temple)	53.5	7.3	2
	Todaiji-nandaimon (temple)	108.0	19.2	18
	Todaiji-nandaimon (temple)	89.8	13.4	4
	Todaiji-nandaimon (temple)	89.8	8.2	4
	Todaiji-nandaimon (temple)	71.6	7.3	4
	Uwajimajo-tenshu (castle)	60.0	7.5	1
	Uwajimajo-tenshu (castle)	60.0	6.2	1
Cercidiphyllum japonicum	Hirosakijo (castle)	61.6	10.5	1
Tsuga sicboldii CARR.	Himejijo-daitenshu (castle)	94.7	12.0	1
Pinus thunbergii	Matsuyamajo-tenshu (castle)	55.3	6.3	10
	Uwajimajo-tenshu (castle)	64.2	6.2	1
	Kitada-ke (folk house)	60.0	18.6	1
	Goto-ke (folk house)	68.3	6.3	3
Abies firma	Himejijo-daitenshu (castle)	105.7	15.0	1
	Himejijo-daitenshu (castle)	105.7	25.9	1
unknown	Todaiji-shoro (temple)	91.7	6.5	4
	Todaiji-shoro (temple)	97.4	8.8	1
	Todaiji-shoro (temple)	110.5	9.4	2
	Daigoji-gojunoto (temple)	83.8	11.5	1
	Kumamotojo (castle)	56.7	10.3	1
	Koutijo (castle)	56.8	9.1	1
	Edojo (castle)	63.1	6.6	1
	Edojo (castle)	58.2	13.6	1
	Himejijo-daitenshu (castle)	55.3	7.9	5
	Himejijo-daitenshu (castle)	55.3	10.5	3
	Himejijo-daitenshu (castle)	60.3	9.7	3
	Himejijo-daitenshu (castle)	55.3	10.0	12
	Himejijo-daitenshu (castle)	55.3	11.8	8
	Himejijo-daitenshu (castle)	55.3	19.1	3
	Himejijo-daitenshu (castle)	57.5	7.5	1
	Hirosakijo (castle)	86.8	10.3	1
	Matsuyamajo-tenshu (castle)	60.0	9.8	1
	Matsuyamajo-tenshu (castle)	60.0	7.3	5
	Masudake (folk house)	65.2	9.5	10
	Isa-ke (folk house)	70.4	10.5	1
	Imanishi-ke (folk house)	60.0	7.9	3
	Kyu-okada-ke (folk house)	70.4	8.0	1

Table 2 The names of materials and the size of them in Figs. 4 and 5

No.	Materials	number of materials	diameter or width (cm)	log or square materials	length(m)	Explanations
1	Hashira (Naijin)	4	64	log	8.2	pillars at the center of a building
2	Koryo (Gaijin)	4	55	square	7.6	arch beams at *moya* (the outside)
3	Koryo (Naijin)	2	45	square	7.3	arch beams at *moya* (the inside)
4	Hashira	18	100	log	19.2	pillars of a building

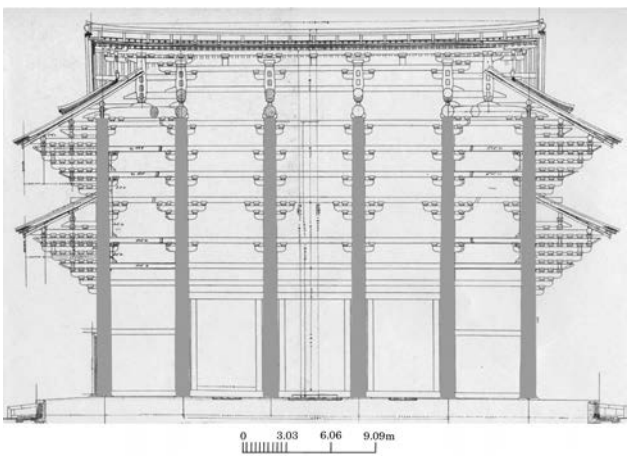
a. The picture of Jodoji-Jododo



b. Elevation of Jodoji-Jododo

Fig. 4 The picture of Jodoji-jododo and elevation of Jodoji-Jododo
Original Figure, Office of the Repair Committee of the jododo at the Jodoji Temple, a National Treasure (1959).

a. The picture of Nandaimon at Todaiji-temple



b. Elevation of Nandaimon

Fig. 5 The picture of Nandaimon at Todaiji-temple and elevation of Nandaimon
Original Figure, Office of the Repair Committee of the Nandaimon at the Todaiji Temple (1930).

Table 3 Standing tree size necessary to get large diameter and long materials

Name	N	raw wood		standing tree	
		length(m)	diameter(cm)	H(m)	DBH(cm)
Jodoji-Jododo (temple)	4	8.2	71.6	32.6	90.7
Jodoji-Jododo (temple)	4	7.6	64.7	31.4	81.5
Jodoji-Jododo (temple)	4	7.0	64.7	31.2	80.4
Jodoji-Jododo (temple)	4	9.6	64.7	31.8	84.9
Jodoji-Jododo (temple)	2	7.3	53.5	29.2	67.5
Todaiji-nandaimon (temple)	18	19.2	108.0	39.2	161.7
Todaiji-nandaimon (temple)	4	13.4	89.8	36.1	123.6
Todaiji-nandaimon (temple)	4	8.2	89.8	35.1	112.6
Todaiji-nandaimon (temple)	4	7.3	71.6	32.4	89.0
Uwajimajo-tenshu (castle)	1	7.5	60.0	30.5	75.7
Uwajimajo-tenshu (castle)	1	6.2	60.0	30.2	73.5

N, materials number; H, total height of tree; DBH, diameter at breast height of tree.

but isn't included in large diameter and long materials. It is because that *Cryptomeria japonica* is used as the general material rather than the large diameter and long material. The most important tree species which is used for the wooden cultural buildings was *Chamaecyparis obtusa*. Even at Kiso area where a large-sized Japanese cypress trees still can be found, it is extremely difficult to secure a supply of trees having a DBH larger than 150 cm. Using this technique, the material which applies for repairing can choose in the field.

Showing information of available materials for repairs, it is helpful for the repair technical expert to figure out material quantities in a forest. It can be an indicator to make a plan of priority order and time for repair. As for the forester, it can be effective to estimate available material supplied and to preserve better standing wood. As for a construction side, on the other hand, it is necessary to indicate a material demand considering repairing period and change rate. In addition, as for the forester side, it needs to check the large diameter and long materials in forests.

Hereafter, the present state of large trees should be assessed. Furthermore, a relatively large forest area should be bequeathed for the purpose of securing a permanent supply of large-sized trees having a required good-quality. Our next tasks are to follow up the growth of the prospective trees in forests.

This study joins between the situation of the foresters and that of the repair technical experts. In addition, this is the basic research to make smooth the procurement of the large diameter and long material for repair.

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Article

Outdoor and Nature Experiences in Forests for Forest Education: Contents of Activities and Forest Place in Hachioji, Tokyo, Japan

Mariko Inoue* and Yasuhiko Oishi*

ABSTRACT

Recently, forest education, which the Forest and Forestry Basic Act describes "promoting the use of forests for education", has been attracting attention. For its part, the Forestry Agency started to promote "Forest Environmental Education" and "Education for Wood Products Use". There are a wide variety of activities, but the actual types of activities in forests have not been understood. So sites in forests for forest education have not yet been considered. In order to gain a comprehensive understanding of the forests for forest education, outdoor and nature activities in forests were examined as actual activities of forest education. In this study, we analyzed the content of activities in forests and the places for activities through a questionnaire survey on outdoor nature activities in forests in Hachioji, Tokyo, Japan, and analyzed the relationship between the content of forest activities and places for activities. Due to the diversity of forest type and land use in this city, there should be many different type of forest activities. We sent various groups a questionnaire which were considered to be involved with forests activities, and then analyzed the contents of activities in forests, forest types and places for the forest activities through cross-tabulation. The survey started by asking whether any activities had been implemented, and if so, asking the details of the three main activities. We sent the questionnaire to 467 groups, of which 215 (46.0% of the total) responded in 2006. A total of 129 groups listed activities in forests (60.0% of the respondents). And 224 actual activities were recorded. We analyzed 209 activities implemented in Hachioji by 103 groups, without incomplete example data. The results of our investigation on the actual conditions revealed a wide variety of 13 kinds of forest activities. Every activity was carried out in all forests types, but *zouki-bayashi* was used most frequently. Regarding site type, public places such as parks were used most frequently. To consider the relationship between contents of activities and forests, forest activities were characterized mainly by the use of forest sites, based on the ownership and the need to obtain permission for use. Forest activities tended to use forest sites related forest use form: Use-type (a) with no change to the forest such as walking/hiking was implemented mainly in "open areas"that allowed public access. Use-type (b) with a direct impact on forests was implemented mainly in "closed areas"with restricted use. Use-type (c) was mainly implemented in specially designated facilities. Another activity was held in various places with little impact on forests. Use-type (a) was most common. In conclusion, we considered that the content of forest activities is closely related to the use of the forest; especially the impact on forests from forest activities is a major factor. If forestry works were more widespread, it would be necessary to keep forest places where direct impacts on forests in open areas were allowed. Furthermore, it should be necessary to analyze the impact of each kind of activity on forests.

Keywords: forest education, outdoor experiences, nature experiences in forests, contents of activities, forest types

Corresponding author: Mariko Inoue
E-mail: imariko@ffpri.affrc.go.jp
* Tama Forest Science Garden, Forestry and Forest Products Research Institute, 1833-81 Todori, Hachioji, Tokyo 193-0843 Japan

INTRODUCTION

Forest education has recently started attracting attention (INOUE, 2007). The Forest and Forestry Basic Act refers to "promoting the use of forests for education" (FORESTRY AGENCY, 2001), and the Forestry Agency has already started promoting

such campaigns as "Forest Environmental Education" and "Education for Wood Products Use" (FORESTRY AGENCY, 2006). Outdoor nature activities in a forest setting are diverse and have long been implemented for recreational and educational purposes. Foresters, forestry technicians, primary school teachers, social education officers, and forest instructors are among the many people who promote forest activities. The National Forest in Japan provides a natural setting for school field trips under the program "Fun Forest for Field Games and Environmental Education" (FORESTRY AGENCY, 2006).

However, according to previous studies, full consideration has never been given to places for forest education activities in Japan. Studies have been conducted on forest education, such as by SEKIOKA (1993; 1994) and KAMIIZAKA (1998), and the history and present status of forest and forestry education have been reported by ENDO (1995), SEKIOKA (1999), and HAYAJIRI and HAYASHI (2006). Several new environmental education programs on forests have been reported (HIROSHIMA *et al.*, 2006; INOUE and OISHI, 2008) and the contents of forest education have been classified into four elements (INOUE and OISHI, 2010). Public participation in forest management and sites for forest education were investigated by YAMAMOTO (1998) and activities at experimental forests for schools were reported by TAKEMOTO *et al.* (2001). However, there is little information to provide a comprehensive understanding of the places for forest education activities. Consequently, forest sites used for educational purposes have not been considered as an object of forest management. In order to advance forest education, it is essential that forest management including conservation recognize the use of forest education. To develop appropriate forest management plans for forest education, it is necessary to investigate the actual status of outdoor and nature activities in forests to fully understand forests for forest education. A wide range of outdoor nature activities were examined as actual activities of forest education.

In this study, we selected Hachioji, Tokyo, Japan as the site for our case study on various outdoor and nature activities in forests. Due to the diversity of forest type and land use in this city, there should be many different types of forest activities. We analyzed the relationship between the content of forest activities and places for activities through a questionnaire survey. This study is the first step towards establishing a system for utilizing forests for educational purposes.

METHODS

We analyzed the present status of outdoor nature activities in forests in terms of the content of forest activities and the places for activities through a questionnaire survey conducted in Hachioji, in order to gain a comprehensive understanding of the forests for forest education.

The study site was located in the city of Hachioji in Tokyo Metropolitan Prefecture, which varies in land use and forest type. Hachioji has a population of about 540,000 and an area of 186.31 km^2. It is about 40 km west of the center of Tokyo, and is one of the many commuter towns in the region. Heights above sea level ranges from 63 to 862 m. Forests in Hachioji occupy 42% of the total land area. Hilly land, forestry areas, and municipal parks rich in greenery and green tracts of land occupy 61% in total (Fig. 1. Data is from HACHIOJI CITY, 2010). The famous Mt. Takao is easily accessible by public railway from the center of Tokyo, and the surrounding low mountains are very popular hiking destinations that are also easily accessible. In this area, various green tracts of land are close to residential areas, so outdoor nature activities can be held in one day. The forests covering the mountains are classified into evergreen broadleaf including *Castanopsis sieboldii* and *Quercus glauca*, coniferous plantation including *Cryptomeria japonica* and *Chamaecyparis obtusa*, and deciduous broadleaf including *Quercus acutissima* and *Q. serrata*.

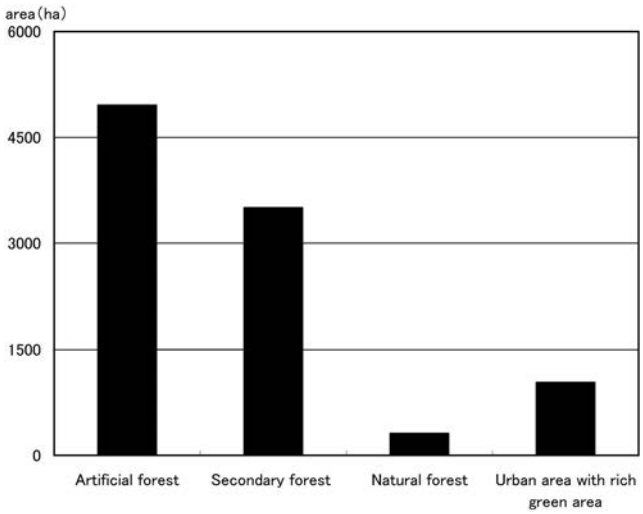

Fig. 1 Distribution of actual vegetation in Hachioji (HACHIOJI CITY, 2010)

The targets of the questionnaire survey were organizations and individuals considered to be involved in forest activities in Hachioji, according to a preliminary survey on sectors implementing outdoor nature activities (OISHI, 1998). Questionnaires were sent to 467 groups including various administrative offices (totaling 58 including environment, forestry, parks, education and sightseeing), schools (totaling 185 including 33 kindergartens, 69 elementary schools, 44 junior high schools, 20 high schools, 15 universities and 4 weekly children's schools), social education for children (totaling 147 including 83 nursery schools, and 64 children's centers), corporations including Boy and Girl Scouts (total 21), private corporations including woodworking plants (total 18), and citizens' groups (total 38).

The questionnaire survey started by asking whether or not any activities had been implemented, and if so, the details of the three main activities, i.e., title and content, geographical place, forest type and ownership. Title and place of activity

were asked for as descriptive answers. Note that the answers to the questionnaire survey depended on the subjectivity of the respondents. The content of activities was selected from among 13 different choices (multiple-answer format) (INOUE *et al.*, 2010):

(1) Contact with nature
(2) Recreational use of forest area
(3) Ecology conservation
(4) Nature observation
(5) Collection of natural products for observation and learning
(6) Collection of natural products for utilization
(7) Natural environmental maintenance
(8) Provision of facilities in forests
(9) Forestry work
(10) Handicrafts
(11) Outdoor life
(12) Creative activity
(13) Outdoor sports

Forest type was selected from among three choices (multiple-answer format): (1) Artificial forest (plantation), (2) *Zouki-bayashi* (coppices recognized as *satoyama*), and (3) Natural forest. Here, *zouki-bayashi* is not a technical term for the forest type, but is a type of secondary forest formerly managed for firewood and charcoal production, and is familiar to local residents. This forest type is found in hilly areas predominantly composed of deciduous broadleaf trees (Fig. 1). Therefore, we set *zouki-bayashi* as one of the choices.

Ownership was selected from three choices (multiple-answer format): (1) Public place (e.g., park), (2) Own property, and (3) Other ownership. The answers regarding forest type and land ownership were dependent on the subjectivity of the respondents, so we checked geographical places by the descriptive answers.

This survey was implemented in November 2006. We sent the questionnaire to the 467 groups, and received 215 (46.0% of the total) responses. We analyzed the content of forest activities in Hachioji, forest types and places for forest activities through cross-tabulation. We analyzed the relationship between the content of forest activities and the places for activities, and then considered the status of forests for educational activities.

RESULTS

The results of the questionnaire survey on forest activities revealed that a total of 129 groups including individuals were involved in forest activities (60.0% of the respondents). The number of actual activities was 224 in total. We were removed unsuitable activities due to implementation outside Hachioji, incomplete sample data, duplicate data, or unsuitable forest activities, i.e., agricultural work and river monitoring. Then, we analyzed 209 activities that were implemented in Hachioji by 103 groups. Junior high schools implemented forest activities, but all activities were held outside Hachioji or the response data was incomplete.

Classification of the 103 groups conducted the 209 activities was as follows: various administrative offices (totaling 32 activities including environment, forestry, parks, education and sightseeing), schools (totaling 61 activities including 19 by kindergartens, 23 by elementary schools, 7 by high schools and 12 by universities), social education for children (totaling 45 activities including 22 by nursery schools and 23 by children's centers), corporations including Boy and Girl Scouts (total 12 activities), private corporations including woodworking plants (total 19 activities), and citizens'groups (total 40 activities).

Various groups implemented forest activities. And since the forest areas are within the city, all activities could be held in one day, except for those designed for an extended stay as in the case of camps. Places for forest activities included not only forestry areas but also municipal parks and, grounds rich in greenery and hilly land near residential areas.

Contents of Forest Activities

Table 1 shows the keywords for the contents of forest activities classified into the 13 different kinds, and others. The contents of forest activities in actual practice revealed a wide variety of activities. Examples of the main keywords for forest activities appearing several times are as follows: mountain climbing and hiking, camping, games for get close to nature, many kinds of nature observation, and timber-felling and other types of forestry work. Also there were included school trips, walking and daily strolls, which were not usually recognized as forest activities. Since these activities were implemented in rich green areas, we considered them as types of outdoor experiences and forest activities. Distinguishing activities were those related to learning about forests and forestry, environmental leadership training and about experiences as a trainee monk since Mt. Takao is a holy mountain with a Buddhist temple situated at the top.

Figure 2 shows the amount of each of the 13 kinds of forest activities and other activities obtained from the multiple-answer questionnaire. Each of "Contact with nature" and "Nature observation" accounted for more than half of all activities.

Forest Type for Forest Activities

We examined the forest types used for forest activities. Figure 3 shows the forest type of the places where forest activities were carried out (multiple-answer). *Zouki-bayashi* was used most frequently in comparison to natural and artificial forests. Compared with the actual distribution of forest types in Hachioji (Fig. 1), *zouki-bayashi* was used frequently, 57% of the total forest activities, even though secondary forests such as *zouki-bayashi* occupy only 32% of the total actual vegetation in Hachioji. *Zouki-bayashi* is distributed in parks, and is mainly covered by *Quercus serrata*. Artificial forests and coniferous

Table 1 Keywords for outdoor nature experiences in forests

Contents	Keywords for actual activities
(1) Contact with nature	games for get close to nature, stroll, school trip, play, forest therapy, tree climbing, adventure and exploration
(2) Recreational use of forest area	excursions to view the autumn leaves, recreational working
(3) Ecology conservation	Investigation for wildlifr, vegetation survey or environmental survey for conservation, preservation activities include mowing
(4) Nature observation	tree gazing, bird watching, observation of insects, observation tour
(5) Collection of natural product for observation and learning	collection of acorns, fallen leaves, or insects for learning
(6) Collection of natural products for utilization	collection of firewood, nuts or berries for utilization, mushroom picking, gathering foods
(7) Natural environmental Maintenance	sweeping fallen litter, cleaning,conservation of coppice forests
(8) Provision of facilities in forests	building a tree house, constructing a walkway
(9) Forestry work	tree planting, brushing, pruning, thinning, cleaning, cutting, mushroom cultivation
(10) Handicraft	vegetable dyeing, woodwork, bamboo work
(11) Outdoor life	camping, outdoor cooking, cooking and eating natural foods
(12) Creative activity	outdoor artistic activity
(13) Outdoor sports	mountain climbing, hiking, picnics, mountain bike
(14) Others	experience of a trainee monk, promotion about forests and forestry, training environmental leaders

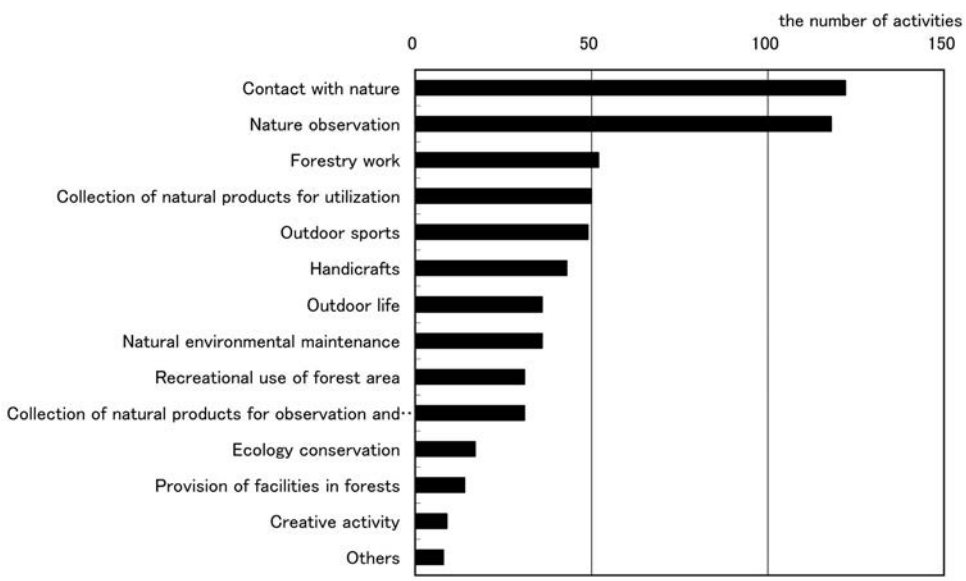

Fig. 2 Amount of each forest activity (multiple-response)

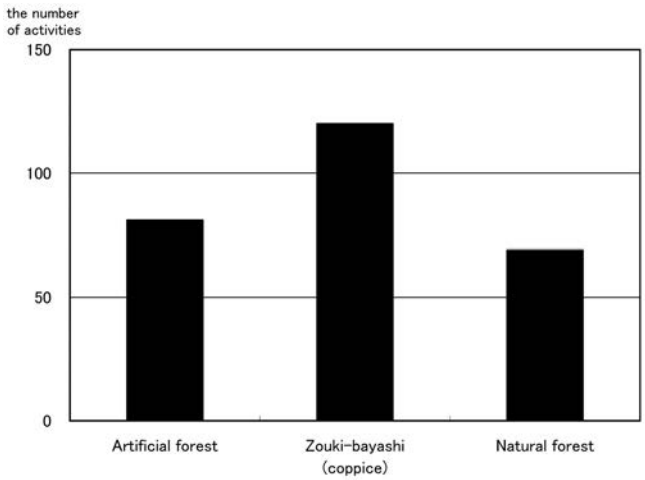

Fig. 3 Frequency of each forest type used for forest activities (multiple-response)

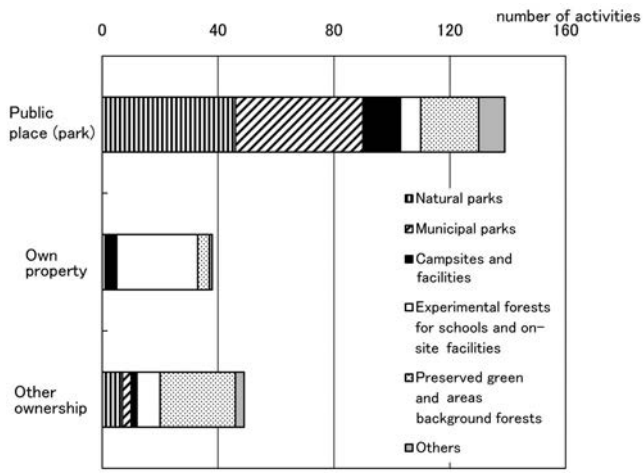

Fig. 5 Amount of forest activities classified by ownership of the forest places

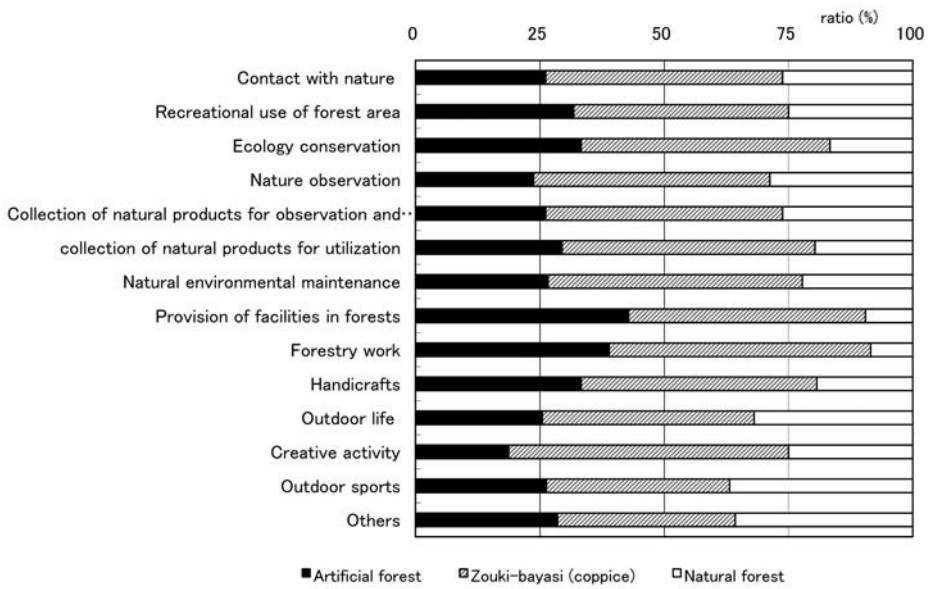

Fig. 4 Ratio of used forest types for each forest activity (multiple-response)

forests range widely and are covered by *Cryptomeria japonica* (Tokyo Metropolitan Government, 2009), were not used in proportion to the ground cover. Natural forests were used frequently instead of small area.

Figure 4 shows the ratio of forest types for each of the forest activities (multiple-answer). All types of forest activities were implemented in all forest types; for example, forestry work and provision of facilities in forests were practiced mainly in artificial forests and *zouki-bayashi*. All types of forests were recognized as places for forest activities, although the forest types in the answers were not exactly correlated to each other due to the subjectivity of the respondents.

Forest Site for Forest Activities

Ownership of the forest sites was examined. Figure 5 shows the number of forest used for forest activities classified by ownership (multiple-answer). Public places such as parks were used most frequently. According to the data on green tracts of land in Hachioji, municipal parks occupy 4.4% (826 ha) in total (Hachioji City, 2010), and there are four prefectural natural parks occupy more than 4,400 ha (Tokyo Metropolitan Government, 2009).

To obtain further details about the forest places for forest activities, they were classified based on the description of the geographical place for forest activities, consider to the owner-

ship and the need to obtain permission for use. There were listed 68 place names where the 209 forest activities were held. There were six categories of site format for forest activities as follows:

Natural parks: Public places with free access and hiking trails. Mt. Takao and three other places were included in this category, and they all occupy a large area.

Municipal parks: Public places with free access and green zones. This category included eleven city parks and five metropolitan parks. All parks include groves or coppices, three parks have a visitor center, three parks have a conservation area or coppice management area, and five parks have parking lots (Tokyo Metropolitan Park Association, 2010). Large parks are mainly covered with *zouki-bayashi*; the largest park is 46 ha in area.

Campsites and facilities: Public or private places for special use. Here, users are required to make reservations and/or pay a fee. There were three campsites and one botanical garden on hilly land. This category included campsites with accommodations allowing overnight stay.

Experimental forests for schools and on-site facilities: Public or private ownership. In this category, 20 places were mentioned. In this place, use of forests is usually restricted to the members.

Preserved green areas and background forests: This category included preserved green areas, and forests for which the location was clear but ownership was not. In this category, 18 places were mentioned including five preserved green areas. This type of place usually requires permission for use.

Others: This included places for which the location and ownership were unclear but they are situated in Hachioji; for example, mountainous areas in Hachioji used for climbing/hiking or hilly land used for daily walks. In this category, there were 6 places.

Figure 5 shows the frequency of forest activities according to ownership and classified by these six kinds of forest site formats. Public place (park) included "National parks", "Municipal parks" and "Campsite and facilities". Own property was predominantly "Experimental forests for schools or on-site facilities". Other ownership was predominantly "Preserved green areas and background forests".

Relationship between Contents of Forest Activities and Places for Activities

We analyzed the relationship between the content of activities in forests and the forest site format mentioned above. Figure 6 shows the ratio of forest places by site format for each forest activity. Almost all activities were held in each site format, except "Ecology conservation", "Creative activity" and "Provision of facilities in forests".

The trend in type of forest site used for each activity could be characterized. Forest activities are arranged by the total ratio of "Natural parks", "Municipal parks" and "Campsites and facilities" in Fig. 6. The majority of activities located in the upper part of Fig. 6, which were held in "Natural parks", "Municipal parks" or "Campsites and facilities", were "Outdoor sports", "Contact with nature", "Recreational use", "Na-

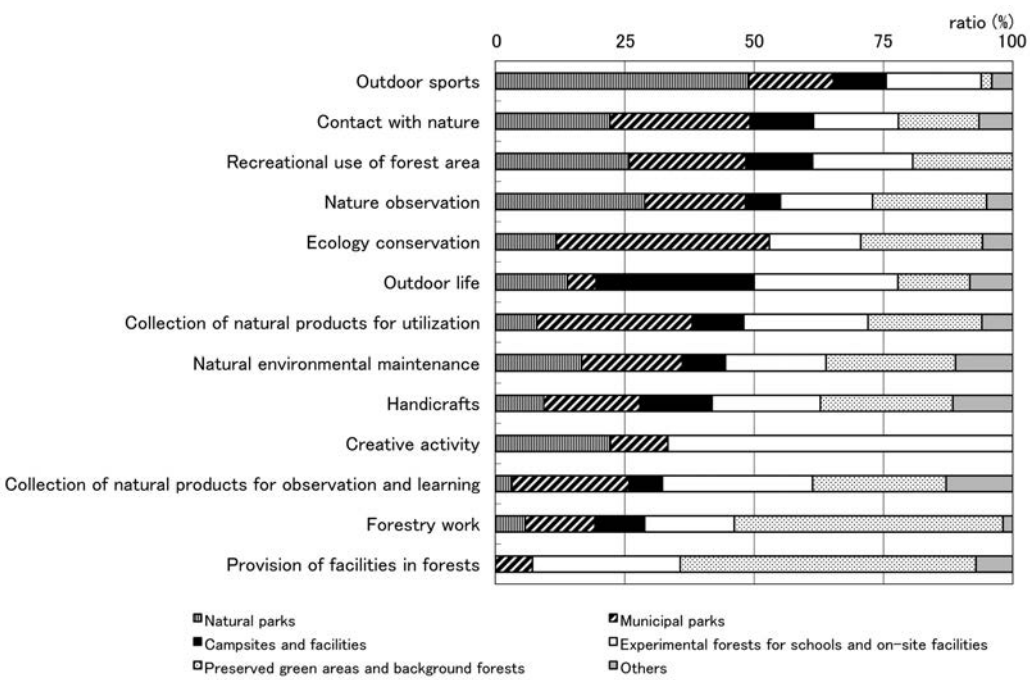

Fig. 6 Ratio of types of site format classified by forest activities

ture observation", "Ecology conservation", and "Outdoor life". "Outdoor sports" was mainly held in "Natural parks". "Outdoor life"was mainly held in "Campsites and facilities". "Ecology conservation" tended to be held in "Municipal parks". These activities were held mainly in public areas for public use.

On the contrary, the majority of activities located in the lower part of Fig. 6, which were held mainly in "Experimental forests for schools or on-site of facilities" and "Preserved green areas and background forests", were "Provision of facilities in the forest", "Forestry work", "Collection of natural products for observation and learning" and "Creative activity". "Provision of facilities in the forest" and "Forestry work"were mainly held in "Preserved green areas and background forests". "Creative activity" was mainly held in "Experimental forests for schools or on-site of facilities". These activities were held mainly in restricted or permission required areas.

In addition, "Handicrafts", "Natural environmental maintenance", and "Collection of natural products for utilization" were held in all kinds of site formats. Thus, forest activities were characterized mainly by the use of forest sites. Activities were divided by whether they were mainly held in public places with free access, or mainly held in restricted places, or held in various places. In other words, forest activities were divided by whether they were mainly held in public places or not.

To consider the relationship between forest activities and forests, this result was compared with previous results for forest activities. OISHI and INOUE (2006) divided forest activities into four types of forest use form including six kinds according to contact with the forest. The six kinds of forest use form were as follows:

Direct use form: Activities held in a forest include contact with the forest. This activity was necessary to be held in forests. This use included two kinds divided by the degree of impact on forests.

- Direct use form 1 with no impact on forests: Activities in a forest, with little impact on the forest such as observation, walking and forest recreation.
- Direct use form 2 with strong impact on forests: Activities in a forest accompanied by a strong impact on the forest, such as cutting trees, collecting forest products, building facilities and installing a birdhouse.

Environmental use form: Activities held near forests using forests as natural scenery or activity area. These activities could be held outside forests, but forest areas were often used. This use included two kinds divided by degree of environmental modification.

- Environmental use form 1 with no change to forests: Activities near/in a forest, with little change to the environment such as hiking and cross-country skiing.
- Environmental use form 2 in facilities: Activities held in facilities such as a camping site, a ski slope and an adventure playground.

Indirect use form: Activities using forest resources such as woodwork and eating bamboo shoots. This use need not be held in forests, so it could be held inside or outside forests.

Theme use form: Creative activities with themes related with forests, for example, based on art or music about forests. This use could be held inside or outside forests.

The 13 kinds of forest activities in this study were applicable to the following forest use forms:

Direct use form 1: "Contact with nature", "Recreational use" and "Nature observation". Some activities included in "Ecology conservation" and "Natural environmental maintenance" were applicable to this form, such as investigations of wildlife.

Direct use form 2: "Provision of facilities in the forest", "Forestry work", "Collection of natural products for observation and learning", and "Collection of natural products for utilization". Some activities included in "Ecology conservation" and "Natural environmental maintenance" were applicable to this type, such as mowing and timber-felling for nature conservation.

Environmental use form 1: "Outdoor sports".

Environmental use form 2: "Outdoor life", mainly held in camping sites.

Indirect use form: "Handicrafts"

Theme use form: "Creative activity"

The indirect use form and the Theme use form were held in a forest or green spaces in this study because forest activities in this study excluded those activities operated outside forests and green areas.

Comparing our results for forest site use in forest activities and these six kinds of forest use form by OISHI and INOUE (2006), there are similar classifications. These can be divided into three types and others; applicable to forest use form, forest activities, and mainly forest site use were as follows:

(a) Environmental use form 1 and Direct use form 1, including "Outdoor sports", "Contact with nature", "Recreational use", and "Nature observation", were located in the upper part of Fig. 6. These types of activities were held mainly in "Natural parks" or "Municipal parks". This use type was not accompanied by a strong impact on forests.

(b) Direct use form 2, including "Provision of facilities in the forest", "Forestry work", and "Collection of natural products for observation and learning", were located in the lower part of Fig. 6. These types of activities were held mainly in "Experimental forests for schools or on-site of facilities" and "Preserved green areas and background forests". This use type was accompanied by a strong impact on forests.

(c) Environmental use form 2, including "Outdoor life", was held mainly in "Campsites and facilities".

Other activities, which included the Indirect use form, Theme use form, and both the Direct use type 1 and Direct use type 2, were located in the center of Fig. 6. These activities were held in various sites, and there effects on forests were considered to be not strong. The Indirect use form and

Theme use form, including "Handicrafts" and "Creative activity", could both be held outside forests and were held in easily accessible areas in these results. "Ecology conservation" and "Natural environmental maintenance" including both the Direct use type 1 and Direct use type 2, could be held in conservation areas in parks. "Collection of natural products for utilization" fitted the Direct use type 1, including gathering nuts, acorns and pinecones for handicrafts by children, and it was considered not to have strong effects on forests in these results.

We considered the relationship between forest sites and contact with forests by each use-type activity. Use-type (a) was held without changes to the forest such as walking/hiking, and so its area of operation could be allowed in public places with free access. The Main area of operation of use-type (a) was considered to be "open areas". Use-type (a) was most common. Use-type (c) was mainly implemented in specially designated facilities, and could be allowed for everyone provided reservations were made. On the contrary, use-type (b) was held with a direct impact on forests, and the area of operation could be restricted or could require permission for use. The Main area of operation of use-type (b) was considered to be "closed areas". Another activity was held with little impact on forests, so it could be allowed in various places.

Thus, forest activities trended to use forest sites related to contact with forests. In other words, forest activities were characterized as to whether they could be allowed in "open areas" or not.

CONCLUSIONS

This research focused on the relationship between the content of forest activities and forest sites. To accomplish our objective we examined the present status of outdoor nature activities in forests through a questionnaire survey in Hachioji, Tokyo, Japan to gain a comprehensive understanding of the educational use of forests.

The first stage of our investigation, forest activities in actual practice in Hachioji, comprised a wide variety including walking and daily strolls in rich green spaces. All kinds of forest types were recognized as places for forest activities, but *zouki-bayashi* was used most frequently. This agrees with the result that *zouki-bayashi* is used most frequently at experimental forests for schools (TAKEMOTO *et al.*, 2001). Regarding site type, public places such as parks were used most frequently.

In the second stage, we analyzed the relationship between forest activities and forest sites. Forest activities tended to use forest sites related to forest use form. Use-type (a) with no change to the forest such as walking/hiking was implemented mainly in "open areas" that allowed public access. Use-type (b) with a direct impact on forests was implemented mainly in "closed areas" with restricted use. Use-type (c) was mainly implemented in specially designated facilities. Another activity was held in various places with little impact on forests. Use-type (a) was most common.

To consider the status of forests for educational activities, forest activities of use-type (a), (c) and another activity were available for public use in "open areas", but activities of use-type (b) were limited for use in "closed areas". If use-type (b) activities are to be operated in schools without school forests, it is indispensable to find forests that can be used. Therefore, if use-type (b) activities such as forestry work become more widespread, it is necessary to keep forest places where direct impacts on forests are allowed in open areas. However, it is necessary to consider the impact of each forest activity on forests. Furthermore, forest activities require not only forest use but also guides or leaders for the activities as well as maintenance and management of the forests. It is necessary to inspect the actual relationship between forest activities and forest places through case studies.

In conclusion, our investigation on the status of forest educational activities revealed that all forest types are recognized as places for a wide variety of activities. We consider that the content of forest activities is closely related to the use of the forest; in particular, the allowable impact on the forest by forest activities is a major factor in closed forest areas. Therefore, it is necessary to keep forest places that can be used for various forest activities, if forest activities are needed to be more common. However, the trends in the content of forest activities and forest type were inferred from the multiple-answer questionnaire and depended on each respondent's viewpoint. Therefore, further analysis of forest activities by investigating case studies should be carried out in the future. This study is the first step towards establishing a system for the utilization of forest sites for educational purposes. Research on the impact of each type of forest activity is important for determining the type of forest management needed for forest education sites.

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