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Article

Monitoring Survival Rates of Young Plantation Trees in Mountainous Regions in Japan using LANDSAT TM Data

Yukio Teraoka*[1], Akihisa Hirata*[2], Shigeru Iida*[3], Nobuya Mizoue*[4], Shigejiro Yoshida*[4], Morio Imada*[4] and Susumu Inoue*[3]

ABSTRACT

It has proved difficult to monitor the state of plantations by field observations due to the high costs involved, although the extent of unsuccessful plantations has been increasing. The objective of this study was to develop a method to estimate the survival rates of planted trees in young Sugi (*Cryptomeria japonica*) and Hinoki (*Chamaecyparis obtusa*) plantations by analyzing LANDSAT TM (Thematic Mapper) data. Our hypothesis was that the survival rate of planted trees, which was regarded as closely correlated with canopy coverage of planted trees, could be represented by the digital number of bands or intensity of some index of remote sensing data. The study sites were young plantations (4 to 12 years old) in Kyushu University Forests in Miyazaki which is located in southern Kyushu, Japan (32°22′10″N, 131°10′40″E), within the cool-temperate deciduous zone. Plantations were divided into aspect classes as the minimum units of this study. The method had two main parts. 1) Interpreting survival rates of planted trees on a pair of aerial photographs. 2) Analyzing the relationships between TM data and the survival rates of trees under two models, MODEL I using *NDVI* (Normalized Difference Vegetation Index) and MODEL II using the TM band 3 digital number (*DN*) for detecting the difference in spectra between planted trees and grass. The results showed that: 1) there were big differences in the survival rates according to aspect, and northern slopes had relatively high survival rates compared with southern slopes. 2) It was difficult to estimate the survival rates of planted trees by *NDVI*. 3) The relationship between survival rates and *DN* in TM band 3 showed strong negative correlation with a coefficient of determination of 0.643. Thus, *DN* in TM band 3 appears to be preferable for estimating the survival rates of planted trees. This study thus indicated that TM band 3 approach would be the most effective monitoring method for plantations in inaccessible mountainous regions.

Keyword: unsuccessful plantation, remote sensing monitoring, survival rates, *NDVI*, TM band 3

INTRODUCTION

Under the expansionary afforestation policy after World War II, the area of plantations in Japan has grown to more than 10 million hectares, occupying about 40% of the total forest area. In southern Japan, especially in Kyushu Island, Sugi (*Cryptomeria japonica*) and Hinoki (*Chamaecyparis obtusa*) plantations have expanded, since these species grow fast and produce excellent timber. As the plantation area has expanded, afforestation has progressed to inaccessible mountainous regions located at high altitude and in cool temperate conditions.

The plantations in inaccessible mountainous regions are liable to be under severe conditions because of grazing by Kyushu Deer (*Cervus nippon*), freezing and drought damage (Teraoka *et al.*, 1992a; Inoue and Koizumi, 1996). Therefore, unsuccessful plantations have been increasing, with disappearance of planted trees and invasion by native broadleaf species (Imada and Masutani 1988; Imada *et al.*

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1991). There is a problem of insufficient information concerning the location of unsuccessful plantations, extent of damage and survival rate of planted trees. It has been difficult to monitor every plantation by field observation due to the time and high costs involved. Thus a more cost-effective method was required to monitor young plantations in inaccessible mountainous regions.

Satellite remote sensing has been used for large scale vegetation monitoring not only in forestry research but also for ecology, geography and civil engineering. There have been many studies concerned with vegetation change monitoring and with estimation of biomass and productivity using some kind of vegetation index such as the Normalized Difference Vegetation Index (*NDVI*) (Hobbs and Mooney 1990). The optical remote sensing was based on the assumption that the signature of any object could be deciphered to obtain its important characteristics (Goel, 1989). The spectral reflectances of vegetation types varied because vegetation had varied characteristics in biomass, leaf area, stand, population structure, and so on.

Recently, Awaya *et al.* (1996) expressed the relationship between Landsat Thematic Mapper (TM) digital numbers and spruce (*Picea glehnii*) stand ages in an exponential function, and pointed out that intensity differences in the digital number, which existed between spruce and invading deciduous broadleaf trees, had much influence on spectral patterns. Katoh (1994) also pointed out that deciduous broadleaf trees in fir (*Abies sachalinensis*) plantation influenced the spectral radiance, especially in the leaf-developing season. Furthermore, fir plantation stands that had not reached canopy closure showed a higher spectral radiance than closed stands due to the influence of ground vegetation (Katoh, 1993). These studies suggested that spectral radiance might change according to the proportion of other vegetation types in the plantation. In other words, the spectral radiance of some plantations varied in proportion to the mixture rate of other types of vegetation cover that had a different spectral characteristic from the plantation species.

Therefore, we developed a simple hypothesis that the survival rate of planted trees, which was regarded as closely correlated with canopy coverage of young Sugi and Hinoki, could be represented by a digital number of bands (hereafter; *DN*) or intensity of some index of remote sensing data.

The objective of this study was to examine the validity of the hypothesis, by testing a method of estimating the survival rates of young planted Sugi and Hinoki by analyzing Landsat TM data.

STUDY SITE

The study area was in Kyushu University Forests in Miyazaki (hereafter; Miyazaki Forest) which is located in southern Kyushu, Japan (32°22′10″N, 131°10′40″E), within the cool-temperate deciduous zone. The altitude range is from 700m to 1,476m above sea level. The average annual temperature is 13degrees Celsius at an elevation of 600m a.s.l., and annual precipitation is about 3,300mm (Kyushu University Forests 1986).

The series of plantations has been developed since 1978 under the clear-cutting system in blocks surrounded by shelter belts (Teraoka *et al.*, 1992a). In this system the area of a cutting block is restricted to less than 5 hectares, and each block should be surrounded by a 15-meter wide shelterbelt of natural mixed forest. There were twenty-four clear-cutting blocks whose ages were ranged from 4 to 12 years old in 1991, and each block is the same with a sub-compartment.

Five blocks were selected for this study as shown in Fig. 1. The blocks were planted from 1978 to 1987, and a summary of them is shown in Table 1. The planted species were Sugi and Hinoki, but the mixture rates of both species differed between the blocks because Sugi and Hinoki require different moisture conditions those vary according to slope positions. The initial number of planted trees was 3,000 per hectare.

Each block was divided into one to three aspect classes because the survival rates of planted trees varied with aspect (Table 2). In all, eleven classes were used for this study. The disappearance of planted trees and invasion by broadleaf trees or grass species, mainly Susuki (Miscanthus sinensis), were observed in every class (Teraoka *et al.*, 1992a).

ESTIMATION MODELS

We developed two models to estimate the survival rates of planted trees using TM data.
The first model (MODEL I) involves the estimation of survival rates by *NDVI*. This model is based on the idea that differences in vegetation biomass would be reflected in *NDVI*. An ecological study reported that Susuki, which is a typical grass species, had 5-8 tons per hectare (Iwaki, 1973) and a young Sugi plantation, which was 10 years old, had 40-80 tons per hectare of aboveground biomass (Channell, 1982). There was a clear difference in biomass between plantation trees and grass, and *NDVI* could be used to detect the difference. *NDVI* was computed in the following equation:

$$NDVI = (DN4 - DN3) / (DN4 + DN3)$$

where *DN* indicates a digital number, and subscript numbers mean the TM bands.

The second model (MODEL II) involves estimation of survival rate by TM band 3. This model is based on the idea that leaf-area index (*LAI*), which varies between vegetation types (Satoo 1973), has an inverse relation to *DN* of TM band 3 (Peterson and Running, 1989). In gen-

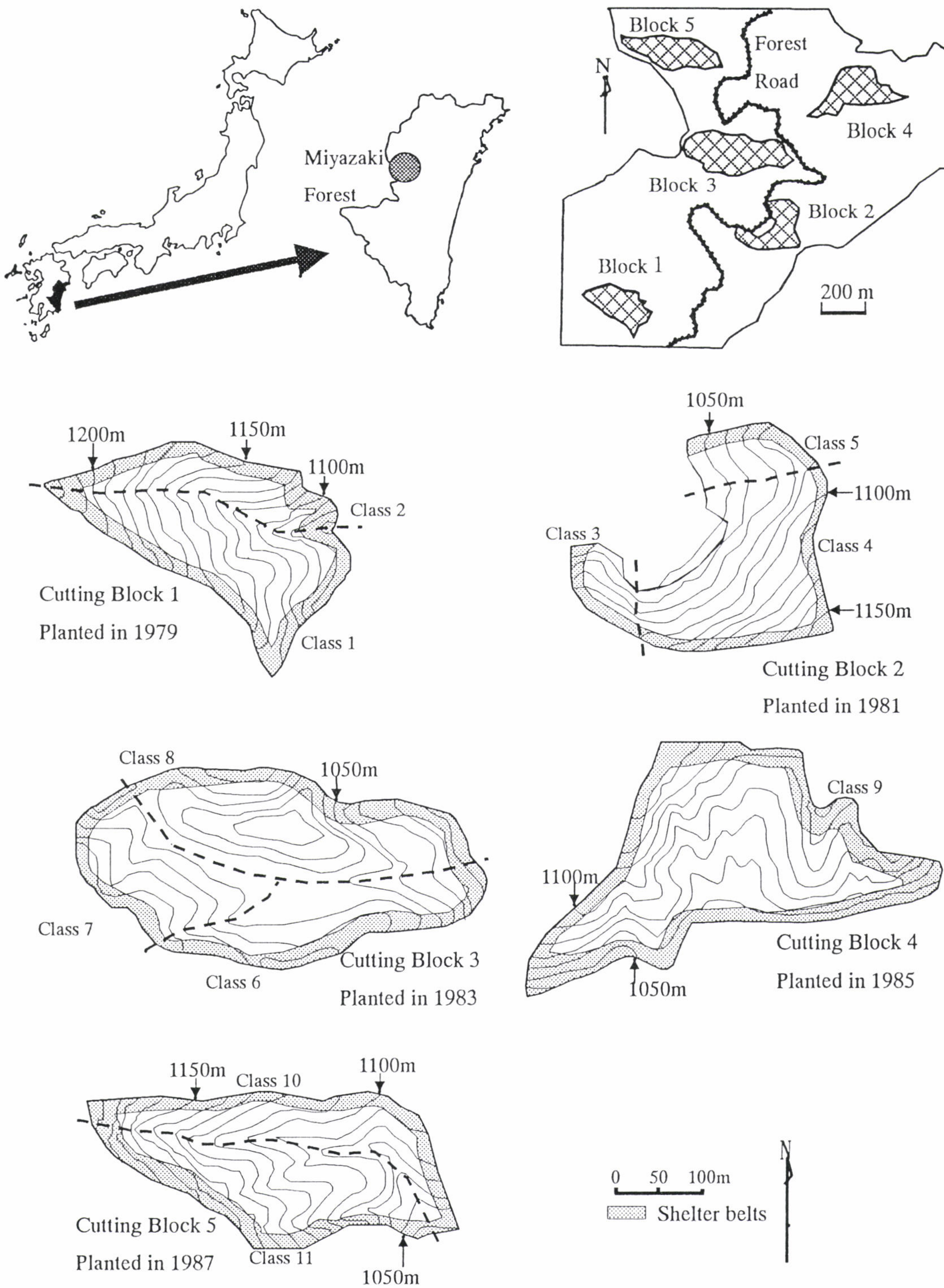

Fig. 1 Description of the 5 cutting blocks and 11 aspect classes with location map.
(Dotted lines indicate borders of classes.)

Table 1 Summary of study blocks.

No.	Planted Year	Species	No. of Aspect Classes
1	1979	Sugi & Hinoki	2
2	1981	Sugi & Hinoki	3
3	1983	Sugi & Hinoki	3
4	1985	Sugi & Hinoki	1
5	1987	Hinoki	2

Table 2 Aspect classes.

Block No.	Class No.	Slope Aspect
1	1	Northeast
1	2	South
2	3	Northeast
2	4	Northwest
2	5	Southwest
3	6	Flat
3	7	Northeast
3	8	Not classified
4	9	South
5	10	Southeast
5	11	Northeast

eral, Sugi plantations have *LAI* values of 5-7, and Susuki populations have *LAI*s of 4-5 (Tadaki, 1976; Iwaki, 1973). Although there is not a large difference in *LAI* value between those two vegetation types, it might be possible to distinguish them by TM band 3. Furthermore, Naito and Aoki (1990) compared the seasonal changes of LANDSAT TM data characteristics of seven vegetation types and reported that there were differences in *DN*s between tree stands and grass population in band 1, 2 and 3 of the TM sensor. Awaya (1990) reported that TM band 3 corresponding to the red wavelength might be suitable for detecting cut-over areas in a Pine forest. Judging from these findings, the TM band 3 would be suitable for distinguishing the spectral difference between grass and trees. Consequently, we used TM band 3 for estimating the survival rates of planted trees in MODEL II.

METHOD

The method of this study was composed of two main parts. The first part was interpreting the survival rates of planted trees on a pair of aerial photographs. The interpreted survival rates were found to be reasonably accurate by field checking (Teraoka *et al.*, 1992b) and assumed to be the real values of survival rates on the ground. The second part was the analysis of the TM data and the survival rates of trees under MODEL I and II. The methods are described in more detail below.

Survival Rates Interpreted on a Pair of Aerial Photographs

The survival rates of planted trees were interpreted on a pair of normal color aerial photographs taken in October 1991. A print enlarged by a factor of two, with an average scale of 1/6,250, was used for the interpretation. The numbers of trees were interpreted at 210 points corresponding to 30m by 30m grid positions on a topographic map for analyzing the spatial distribution of survival rates. The survival rates in all grid positions were averaged, and average values for each aspect class were used in the following analyses.

Analysis of Relationships between Survival Rates and TM Data

The LANDSAT TM image used in this study was taken on 24 July 1992, on path-row 112-38. The TM data was bulk corrected and supplied by the National Space Development Agency of Japan. The study site was covered by 204,800 pixels (512 lines × 400 columns) and extracted from the TM data. The ground resolution was approximately 30m × 30m. The satellite image processing was carried out on TNT-mips ver 5.7 (MicroImages Inc.). Only the plantation area could be selected exactly as a training area comparing with aerial photo interpretations. Therefore, any re-sampling was not done, and the original *DN* values were used as row data in the following analyses.

The aspect classes, which were a minimum spatial unit, were covered by pixels ranging from 4 to 40 pixels, and the average number of pixels was 19.1. Both *DN* values and *NDVI* intensities in each class were averaged. The relationships between survival rates of planted trees and the averaged *NDVI* and *DN* of TM band 3 were analyzed by linear regression.

RESULTS AND DISCUSSION

Survival Rates

The survival rates of planted trees in each aspect class were interpreted on aerial photographs and the results are shown in Fig. 2 . The survival rates ranged from 0.7 to 86.9 %. There were wide differences in the survival rates between classes and also between blocks. The younger plantations showed lower survival rates because the trees suffered serious damage from deer (TERAOKA *et al.*, 1992a). Regarding topographical features, mainly northern aspects generally had a higher survival rate than southern ones in the same block.

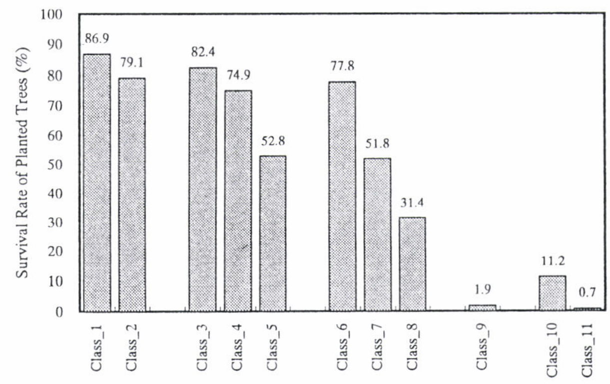

Fig. 2 Survival rates of planted trees in each class by aerial photo interpretation

Analysis of Relationships between Survival Rates and *NDVI*s (MODEL I)

The relationship between the survival rate of planted trees and *NDVI* values for each class is shown in Fig. 3 with the regression line and equation. The coefficient of determination (r-squared value) was 0.374 and the correlation coefficient was significant at the 5% level in a t-test. The biomass, which consisted of planted trees and grass, would be represented in the intensity of *NDVI* on the assumption of MODEL I . There were, however, large deviations from the regression line in class 9 and 11 which had survival rates of 1.9% and 0.7% respectively. The reason was that there was little difference in biomass between the situations of few plantation trees and small tree sizes.

Consequently, MODEL I appeared to be a poor way of estimating the survival rates of planted trees.

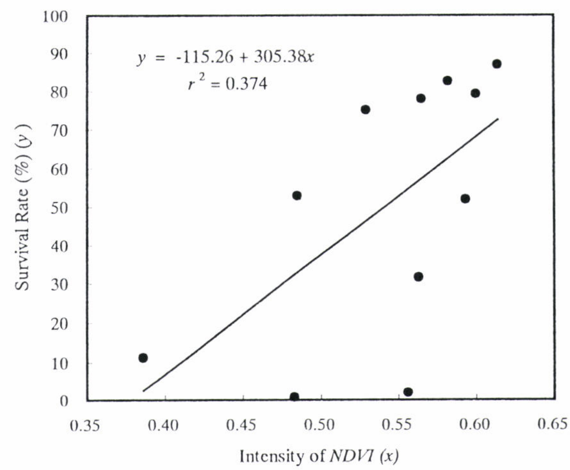

Fig. 3 Relationship between survival rates and average intensity of *NDVI*

Analysis of Relationship between Survival Rates and TM Band 3 *DN*s (MODEL II)

Fig. 4 shows the relationship between survival rates and averaged *DN*s of TM band 3 for each aspect class, with the regression line and equation. A negative correlation was obtained with a coefficient of determination of 0.643, significant at the 1% level in a t-test. The coefficient of determination in MODEL II was significantly higher than that in MODEL I . Furthermore, accuracy of estimation at low survival rates was higher, although class 9, which had a survival rate of 1.9%, still had a large deviation from the regression line. As the survival rate (planted tree coverage) increased, the *DN* of TM band 3 decreased. The reason was that plantation trees, which had a higher *LAI* value than grass, showed lower spectral radiance than that of grass in TM band 3.

On the other hand, there was a problem that the spectral radiance from the same vegetation cover varied

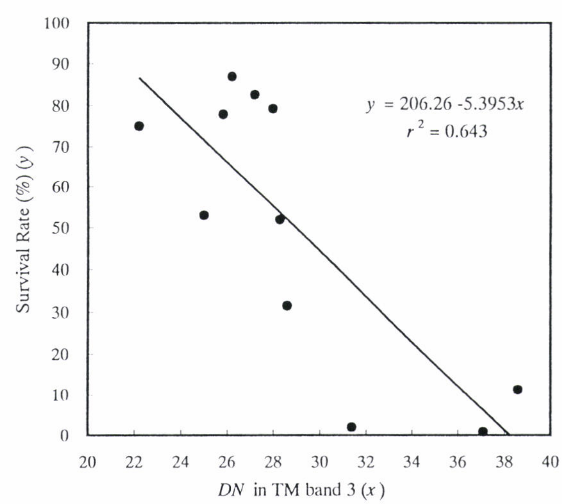

Fig. 4 Relationship between survival rates and average *DN*

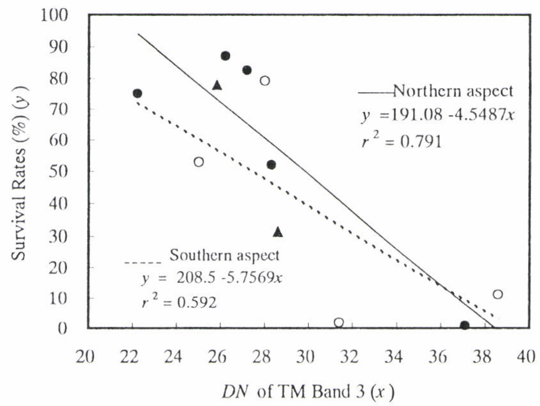

Fig. 5 Relationships between survival rates and average *DN* after separation into two aspect classes
Black and white circles indicate mainly northern and mainly southern aspects, respectively. Black triangles indicate unclassified slopes.

with aspect in the application of the remote sensing data in mountainous regions (Saito *et al.*, 1994; Fujii *et al.*, 1997). The problem was serious when data analysis was carried out only using one sensor band. Therefore, the analysis should be done separately for different aspects. We separated only two broad aspect classes-mainly northern and mainly southern slopes, and analyzed the relationship between survival rates and average *DN* again except for two slopes that couldn't be classified. The re-analyzed result is shown in Fig. 5. There were strong negative correlations both in mainly northern (solid line) and mainly southern (dotted line) slopes with coefficients of determination of 0.791 and 0.592, respectively. In addition, there was no significant difference between the two regression equations according to the result of a t-test with 5% significant level. Thus, we could not distinguish the relationship between survival rates and *DN* in northern and in southern slopes from a statistical viewpoint. Two reasons might be given for the lack of significant difference between aspects. Firstly, slopes were composed of some micro topographical units with varying aspects and gradients. Secondly, there was a ten-fold difference in the numbers of pixel that covered different classes. This suggested that an analysis based on pixel matching might be adequate if a precise correction for topographic influence were possible.

Judging from the results, MODEL II, based on the relationship between *DN*s in TM band 3 and survival rates, is preferable for estimating the survival rates of planted trees.

CONCLUSION

To develop a method for estimating the survival rates of plantation trees using remote sensing data, two models were tested. MODEL I was based on the relationship between survival rates and *NDVI*s. The analysis showed that the correlation between them was weak. MODEL II showed a strong negative correlation between survival rates and *DN*s in Landsat TM band 3. MODEL II, however, should be examined for its validity and developed further because this result was obtained at only one time and in a limited region of the Landsat TM data. It should be noted that MODEL II also require GIS data regarding the locations, species and ages of plantations in large mountainous areas, because an unsuccessful plantation might not be classified as a plantation by remote sensing land cover classification alone.

Although the growing stock of Japanese plantations has been increasing, there has been increasing incidence of unsuccessful plantations located at high altitude and in cool temperate conditions. This study may supply a method to solve the problem of lack of information concerning survival rates in plantations in inaccessible mountainous regions.

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Article

Potential Utilization of New Zealand Wood in Japan

Keiko Nagashima*[1] and Nobukazu Nakagoshi*[2]

ABSTRACT

New Zealand has the potential to become a stable wood supplier to help Japan overcome its projected future difficulties in obtaining wood resources. The basis for this is New Zealand's increasing timber production from monocultural plantations consisting mainly of radiata pine. Presently, Japan uses radiata pine mainly for packaging, with some for plywood production. However, considering the fact that radiata pine is used for many different purposes in New Zealand, it might be possible for Japan to further expand its range of use. The possible areas to improve utilization of New Zealand wood in Japan involve wood used for construction, and civil engineering. However, because it might be difficult to use radiata pine as non-dried pure timber in these areas due to its low quality, such as its relative weakness, processing it into engineering wood is more likely. Considering the utilization of engineering wood imported from New Zealand to Japan, it is likely that New Zealand will face keen international competition in the near future and therefore its market share might not be sustainable. Hence it is critical that both countries cooperate on the issue of improving the technology used for processing radiata pine into engineering wood in order to improve its utilization in Japan.

Keyword: use of NZ wood, radiata pine, stable wood supply, engineering wood

INTRODUCTION

Japan consumes more than a hundred million m^3 of timber per year and is one of the largest timber consumers in the world. Most timber used in Japan is imported: Japan's level of self-sufficiency in timber is only 20% (Forestry Agency of Japan, 1997). Commonly used timbers in Japan include North American wood from the United States and Canada, and tropical wood mainly from Indonesia and Malaysia. These timbers, combined, account for 50% of the total annual timber supply in Japan (Forestry Agency of Japan, 1997). But in recent years, the quantity of these imported logs has been decreasing because of shrinking resources, growing pressure for environmental conservation, and restrictions and prohibitions on log exportation among the wood supplying countries. On the other hand, the amount of sawn timber from these countries is increasing due to their policies of increasing local processing of wood.

This global imbalance in the timber supply adversely affects the ability of Japan's timber industry to obtain wood resources. Although conifer plantations in Japan have become mature and the time for logging is fast approaching, it will be difficult to meet the wood demands of the Japanese industry because of the poor condition of Japan's forestry: prospects for sound management appear to be weakening, and forests have been devastated as a result of poor management caused by the difficult conditions such as falling timber prices and increasing operating costs. Even assuming that the domestic timber supply increases, it is likely that Japan will need to import timber from overseas to meet the high level of consumption.

In this difficult wood supply situation, New Zealand seems to be promising as a country that could provide a stable wood supply. In an effort to conserve the remaining natural forest for environmental and national land conservation, New Zealand has established monocultural tree plantations consisting mainly of radiata pine (*Pinus radiata*) for timber production. The current plantation area

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is about 1.4 million ha and is expanding at the rate of approximately 70 thousand ha per year (New Zealand Ministry of Agriculture and Forestry, 1998). It is predicted that timber production will be 25 million m^3/yr by 2003 and 60 million m^3/yr by 2040 if the plantation areas expand at the rate of 60 thousand ha/yr. (New Zealand Forest Owners Association Inc., 1997). As the estimated future timber consumption in New Zealand would be about 6 million m^3/yr (Donnelly and Whyte, 1994), most of the timber production would be for export. At present, Japan is the largest importer of New Zealand (NZ) wood (New Zealand Ministry of Forestry, 1997), and New Zealand also expects Japan to remain a major destination for its increasing timber supply in the future (Donnelly and Whyte, 1994).

The forestry sector is a developing and promising industry in New Zealand. Employment in this sector is increasing, as is its contribution to the nation's GDP and to New Zealand's exports (New Zealand Ministry of Agriculture and Forestry, 1998). Based on all these facts, New Zealand could become one of Japan's primary wood suppliers in the near future.

Hence, investigating the possibilities for using NZ wood would be a positive step toward overcoming the projected difficulties in obtaining wood resources in Japan. NZ wood is used in Japan mainly for packaging, with some for plywood as a substitute for tropical wood. Its current and prospective uses have been described previously (Nagashima *et al*., 1998). Considering the fact that radiata pine is used in New Zealand for many different purposes (New Zealand Pine Remanufacturers' Association, 1996) including construction (Sugiyama, 1983), it might be possible to adapt radiata pine for other uses in Japan as well. This paper discusses the possibilities and potential consequences of expanding the use of NZ wood in Japan, through an examination of how it is currently utilized. This study aims to find a more beneficial relationship between Japan and New Zealand in the area of timber trade.

POSSIBLE AREAS TO INCREASE THE UTILIZATION OF NZ LOGS IN JAPAN

The areas where the usage of NZ logs in Japan is most likely to increase might be predicted by understanding the contribution of output in each product area using NZ logs towards the determination of the total NZ log import level. Table 1 shows the level of total imports of NZ logs each year from 1986 to 1996, together with the output in each product area containing NZ wood. Multiple regression analysis was done, using the imported amount as the objective variable and the level of output in different areas as explanatory variables. The correlation coefficient

Table 1 NZ log imports and the output for each product area of NZ logs (Imports: Japan Forest Products Journal, *Annual Market Report 1997*, Output: Statistics and Information Department of Ministry of Agriculture, Forestry, and Fisheries, *Report of Timber Demand and Supply*, 1986-1996)

unit:1,000m^3

Year	Imports of NZ logs	Plywood	Construction	Packaging	Wood chip	Civil engineering	Joinery and furniture
1986	260	1	28	462	1	3	1
1987	389	6	27	508	0	15	3
1988	569	0	16	512	0	31	4
1989	763	2	35	623	23	45	7
1990	1,343	103	37	774	0	50	10
1991	1,649	125	56	847	9	56	3
1992	1,861	211	100	832	14	41	4
1993	1,722	315	58	815	10	30	4
1994	1,862	277	56	787	3	45	4
1995	1,866	388	45	814	2	41	0
1996	2,135	405	50	818	0	44	1

Table 2 Correlation Coefficients between imports of NZ logs and output in different product areas (Using the data shown in Table 1)

Year	Impouts of NZ logs	Plywood	Construction	Packaging	Wood chip	Civil engineering
Plywood	0.900					
Construction	0.719	0.528				
Packaging	0.961	0.787	0.737			
Wood chip	0.077	−0.120	0.419	0.201		
Civil engineering	0.692	0.383	0.407	0.776	0.316	
Joinery and furniture	−0.124	−0.392	−0.049	0.044	0.308	0.373

between output in each of these areas was also calculated (Table 2).

The relationship between the t value calculated by regression analysis and the correlation coefficients between usage in each area and the level of NZ log imports is shown in Fig. 1. Because a larger t value means that the area will be more important in determining the level of imports than the areas with smaller t values, it could be said that this indicates the overall contribution which determines the proper level of NZ log imports. The areas with squares in Fig. 1 are those whose P values are smaller than the significance level, 0.05, which means it is a useful area for determining the level of imports. In contrast, the circle-shaped areas are those whose P values are larger than the significance level, and thus they make no or little contribution to the process of determining the level of imports.

As seen in Fig. 1, there is a tendency that areas that show a strong correlation with NZ log imports make a high contribution to determining imports, and areas with weak correlation make a low contribution. However, the contribution of wood used in packaging is quite low although it has a strong correlation. This might be because NZ logs have already been the main resource in this area, and because the demand for packing is stable and does not experience sudden change (NAGASHIMA *et al*., 1998). In addition, it shows that plywood is the area which is the biggest factor in determining NZ log imports followed by civil engineering and construction. It is also clear that if there were an increase in the demands of construction and civil engineering, whose current amounts are not so large but have a high contribution, imports would increase dramatically. Therefore these two areas could possibly be the next targets for New Zealand to promote utilization of NZ logs in Japan. Also, it would be advisable for Japan to consider ways to use NZ logs in these areas, especially for construction which accounts for a large part of the total timber consumption in Japan, to overcome the projected difficulties in obtaining wood resources in the future.

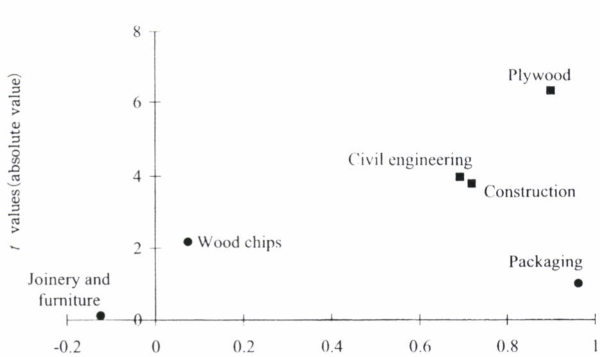

Fig. 1 Contribution to determining NZ log imports (Source: Results of calculation of correlation coefficients and multiple regression analysis based on the data in Table 1)

However, it is difficult to use NZ log as a non-dried pure timber in these areas because of its low quality: wide annual rings, low density, and high number of knots. Therefore, it is more likely to be processed and used as engineering wood.

USING NZ WOOD AS ENGINEERING WOOD

Increase in Supply of Engineering Wood in Japan

In Japan, the supply of engineering wood such as particleboard (PB), fiberboard (FB), and laminated wood (LW) has been increasing in recent years (Figs. 2, 3 and 4). This is due to the demand for highly earthquake-resistant, high-insulation wood, and the pressure for faster house-construction.

Air tight, highly insulated rooms are in demand because air-conditioned houses are very common now. To satisfy these conditions, PB, FB, and LW are considered superior materials to non-dried pure timber due to their resistance to contraction and warping (YASUDA, 1997).

After the Hanshin-Awaji earthquake in 1995, requests

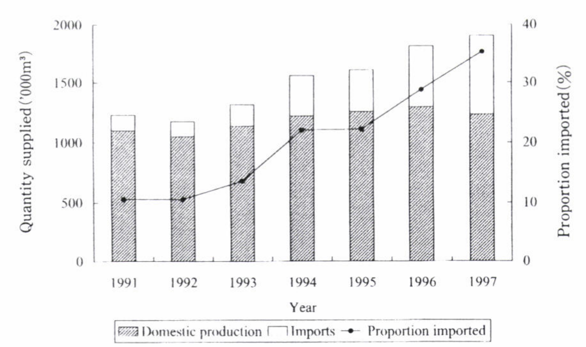

Fig. 2 Supply of particleboard (PB) in Japan (Source: Japan Forest Products Journal, Annual Market Report, 1997 and 1998)

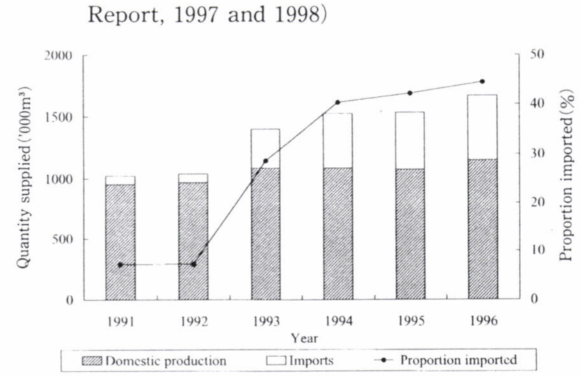

Fig. 3 Supply of fiberboard (FB) in Japan (Source: Japan Forest Products Journal, Annual Market Report, 1997)

for earthquake resistant materials become more frequent, which resulted in a large increase in the supply of PB, FB, and LW (Figs. 2, 3 and 4). As many post and beam constructed houses were destroyed by the earthquake, dissatisfaction with this kind of house was widespread which lead to an increase in the number of 2 × 4 system houses (Fig. 5). This trend was clearly apparent in 1995. While the number of new wooden housing developments decreased, causing 1995 to be most serious time of depression that the domestic timber industry had ever experienced, the number of 2 × 4 system houses increased. As for post and beam constructed houses, a new way of using wood panels positively, for example for box frames, has been developed since the earthquake to make this kind of house stronger (Araya, 1996).

Thus, the opportunities for using engineering wood have increased. However, the Japanese timber industry is not able to accommodate this sudden change in wood demand yet. Rather the demand is being met by increased imports (Figs. 2, 3 and 4).

New Zealand is also producing engineering wood from radiata pine and using high-tech methods of processing based on thorough research. Japan is importing these products from New Zealand. In this section, the capacity of New Zealand as a supplier of engineering wood is explored by considering its current position in this area mainly with respect to PB, FB and LW.

Particleboard

As seen in Fig.6, the level of PB imports from New Zealand is increasing, as is the total level of PB imports. However, although the proportion of NZ wood in the total increased until 1993, since then it has steadily decreased, while the proportion of PB from Canada, Indonesia and Malaysia has increased recently. This can be confirmed by correlation coefficients, which show a negative correlation between the proportion of PB imports from NZ and the proportion from the other three countries: −0.815, −0.692, −0.872, respectively (Table 3).

Although New Zealand is still the fourth highest-contributing foreign supplier of PB to Japan, it will need to pay careful attention to the role of Malaysia, Canada and Indonesia to compete with these countries.

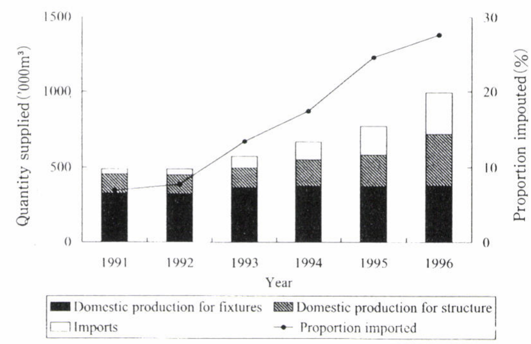

Fig. 4 Supply of laminated wood (LW) in Japan (Source: Forestry Agency of Japan, Forestry Statistics 1998)

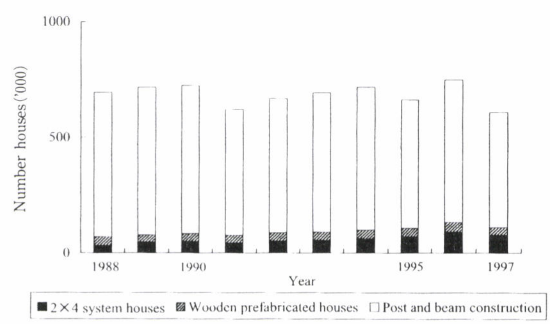

Fig. 5 Number of new wooden houses of different construction styles (Source: Japan Forest Products Journal, Annual Market Report, 1998)

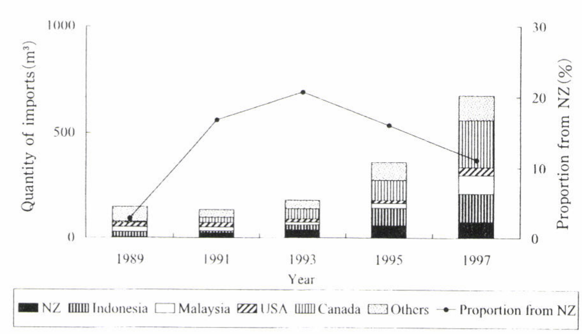

Fig. 6 Imports of PB, by supplying country (Source: Statistical data derived from "Ministry of Finance, Trade Statistics" were supplied by the Forestry Agency)

Table 3 Correlation Coefficients between different foreign PB suppliers' proportion of total imports

Country	NZ	Indonesia	Malaysia	USA	Canada
Indonesia	−0.692				
Malaysia	−0.872	0.250			
USA	0.558	−0.985	−0.081		
Canada	−0.815	0.145	0.994	0.027	
Others	0.853	−0.212	−0.999	0.042	−0.998

Fiberboard

Most of the fiberboard imported from New Zealand is medium density fiberboard(MDF) as seen in Fig. 7.

The total supply of MDF has increased dramatically in the last 7 years. In particular, the imported amount has increased dramatically (Fig. 8). This increase in MDF seems to be caused by the expansion of utilization opportunities, not only because of the increase in the number of 2 × 4 system houses and the new style of post and beam constructed houses, but also because it is now used as a substitute for thin plywood which requires high performance on the surface as well as for fancy board, and for fixtures such as window frames (JAPAN FOREST PRODUCTS JOURNAL, 1997).

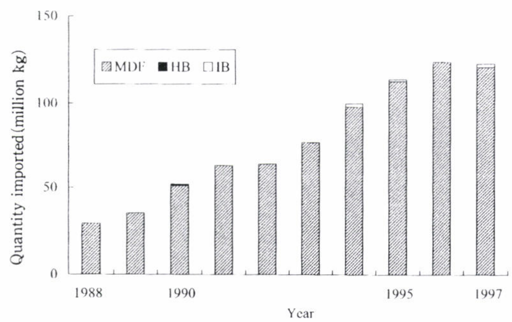

Fig. 7 Imports of FB from New Zealand, by type of FB (Source: Statistical data derived from "Ministry of Finance, Trade Statistics" were supplied by the Forestry Agency)

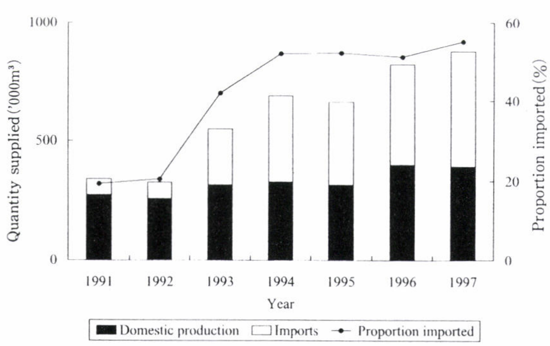

Fig. 8 Supply of MDF in Japan (Source: Japan Forest Products Journal, Annual Market Report 1997)

New Zealand has been the major foreign supplier of MDF to Japan in the past ten years (Fig. 9). Although imports from NZ have been increasing, the proportion of imports from New Zealand has been decreasing since 1992. This happened because imports from Italy, Malaysia and Chile increased. To confirm this, correlation coefficients were calculated based on the change in the proportion of imports from each country in the total since 1992. Strong negative correlation between New Zealand and these three countries was found (Table 4). Malaysia's and Chile's drive to produce and export value-added products must be the main reason for their dramatic increase.

Hence, it seems likely that New Zealand will face a period of keen international competition from those countries that are aggressively exporting value-added products. Therefore, even if New Zealand remains the main supplier of MDF to Japan, its position can not warrant complacency.

Laminated Wood

The increase in the supply of LW in Japan since 1991 has been mainly due to the increase in domestic production

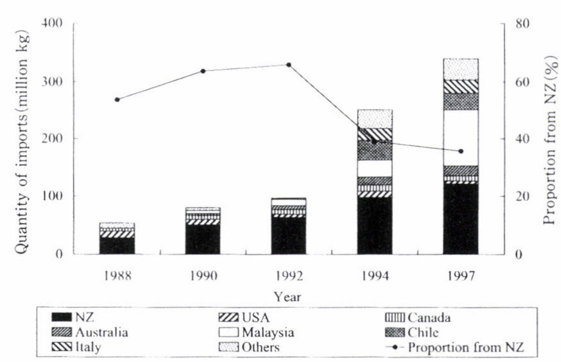

Fig. 9 Imports of MDF, by supplying country (Source: Statistical data derived from "Ministry of Finance, Trade Statistics" were supplied by the Forestry Agency)

Table 4 Correlation coefficients between defferent foreign MDF suppliers' proportions of total imports (Using the data of Fig. 9 from 1992 to 1997)

Country	NZ	USA	Canada	Australia	Malaysia	Chile	Italy
USA	0.8098						
Canada	0.9794	0.9116					
Australia	0.9888	0.8883	0.9986				
Malaysia	−0.6341	−0.9672	−0.7772	−0.7425			
Chile	−0.8604	−0.3978	−0.7397	−0.7746	0.1515		
Italy	−0.9596	−0.6119	−0.8829	−0.9068	0.3908	0.9691	
Others	−0.9557	−0.8766	−0.8766	−0.9011	0.3785	0.9723	0.9999

of structural laminated wood and the increase in imports (Fig. 4).

Imports of structural laminated wood have increased dramatically in the past seven years, especially since 1995, the year of the Hanshin-Awaji earthquake (Fig. 10).

Among foreign suppliers of structural laminated wood, the United States has remained the primary supplier for the past seven years (Fig. 11). However, because imports from Canada, Germany and Sweden increased dramatically from 1995 to 1997, the proportion of United States imports in the total decreased from 94% in 1991 to 39% in 1997. Imports from New Zealand increased until 1995 but decreased after that. The proportion of New Zealand imports in the total also decreased to less than 3 %, although it reached 8 % in 1995. Considering that the level and proportion are both low and decreasing, it could be said that the use of structural laminated wood from New Zealand is unlikely to expand.

The reason for this low usage might be the negative image of radiata pine such as its weakness, which is too prevalent to allow it to be used widely for construction, even if its quality is highly improved by processing. Additionally, it might be because there is more interest in structural laminated wood made from North American wood which is well-known as a resource for construction timber in Japan, and that from European countries supplying "White wood" which has recently captured the attention of the Japanese timber industry (Nakauchi, 1997).

Hence, while the utilization of structural laminated wood has increased in Japan, it could be said that New Zealand is facing a difficult situation because of the competition from other countries' woods which are more attractive to the Japanese domestic timber industry.

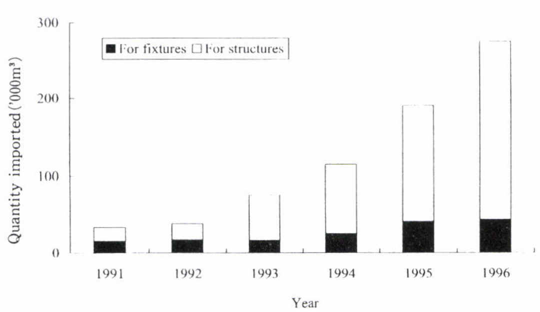

Fig. 10 Imports of LW (Source: Forest Agency of Japan, Forestry Statistics 1998)

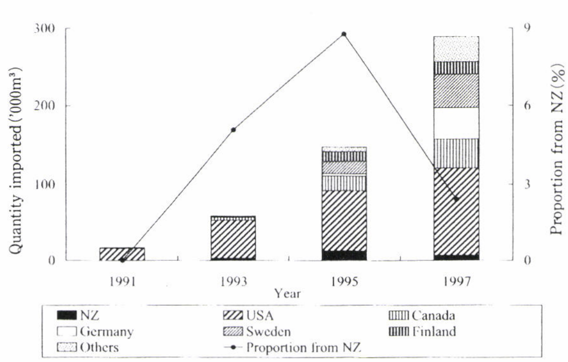

Fig. 11 Imports of structural laminated wood, by supplying country (Source: Statistical data derived from "Ministry of Finance, Trade Statistics" were supplied by the Forestry Agency)

The Prospect of New Zealand as a Supplier of Engineering Wood

Even though New Zealand is the major supplier of MDF, and the fourth largest supplier of PB, its future is not assured. It is likely that New Zealand will face a period of keen international competition in the near future due to the increase in the number of countries that promote the production and export of value-added products. In particular, countries such as Malaysia and Chile, where labor costs are cheaper and therefore production costs are lower, are potential rivals for New Zealand.

The future of structural laminated wood from New Zealand does not appear bright, and great efforts would be needed to increase its utilization in Japan. Understanding why it is not used, for example, and whether there are any problems in quality or suitability for Japanese needs, as well as improving their production methods, would be important for New Zealand's timber industry.

CONCLUSION

The possible areas to improve the utilization of NZ wood in Japan are construction and civil engineering. However, it might be difficult to use it as pure timber in these areas because of its low quality. Therefore, using it as engineering wood might be expected. However, based on the current situation as an engineering wood supplier, the future of New Zealand wood is not secure in this area.

As mentioned before, New Zealand is a promising country for a stable wood supply for Japan, and Japan is one of the most important countries to which New Zealand can export its increasing supply of timber. Based on this fact together with the current situation of NZ wood utilization, it is important for Japan and New Zealand to cooperate on improving the technology of processing radiata pine to make engineering wood.

Through this cooperation, there are advantages for Japan such as the following:

1) Japan could obtain resources not from natural forests but from plantations that are able to achieve sustainable production of timber.
2) Japan might be able to overcome the expected difficulty of obtaining wood resources in the future.

3) Japan could improve its technology for processing engineering wood so it is better able to cope with the current sudden change in wood demand.

As for New Zealand the possible advantages include:

1) a more stable market for the predicted increase in timber production.

2) the ability to make products that meet the demands of Japanese industry better than at present.

As a result of such cooperation, Japan and New Zealand might be able to develop a more rewarding relationship in the area of timber trade.

ACKNOWLEDGEMENT

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Article

Forest Management Problems in Cambodia
— A Case Study of Forest Management of F Company —

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ABSTRACT

A fast growing population and the need for food and forest products coupled with the great demand for wood and rapid economic development in the developing world have brought sustainable forest management under continuous uncertainty. Deforestation in the developing world has been relatively high. But recently, it has been more widely recognized that over-exploitation of forest products and non-forest products is prejudicing the sustainability of the world's forests. Cambodia has been chosen as a case study to test this hypothesis regarding sustainable forest management. There are two main types of forests in Cambodia, namely dryland and edaphic forests, covering a total area of 10.59 million ha or 58% of the total land area. It had been reduced from 12.32 million ha in 1973 as a result of wars and political instability over the last 25 years. Against a background of government instability, great domestic and foreign demands for wood in recent years have resulted in Cambodia's forests being over-exploited. To prove this, a selective 25-year felling cycle system used by F Company was analyzed with the aid of various statistical tools. The analysis shows that although the growing stock of F's evergreen forest is as low as 82 m^3/ha due to illegal logging, the company has exploited 7 m^3/ha or 9% of the total stock. This was 6 percentage points higher than the sustainable cutting rate of Cambodia's evergreen forest. This supports the hypothesis of over-exploitation. The result also shows that there is still a large number of residual trees with diameter less than 45 cm, which are available for extracting over the next 25 years if they are properly managed. Strong enforcement mechanisms for forest monitoring and control are needed to stop illegal logging, to prevent over-exploitation and to manage the residual trees for long-term availability of forest resources.

Keyword: Cambodia, forest management, selective felling, tree classification

INTRODUCTION

Tropical forests have been over-exploited to meet the great demands of fast growing population and rapid economic development in recent years. This phenomenon has put sustainable forest management (SFM) in tropical areas under uncertainty. Foreseeing the danger to the world's forests, the world's forestry leaders met during the Earth Summit in 1992, and pledged to promote and attain SFM. Since then, SFM has regained widespread support as a means of ensuring long-term perpetual supply of wood, and other forest products and services. Several management systems have been implemented to manage the forests, but the best-known systems are clear and selective cutting.

The aim of this paper is to analyze the underlying problems of forest management and provide a framework for SFM in Cambodia. The authors have found it difficult to find the relevant forestry documents for such a study, due to the fact that forestry documents were virtually all burned during the Khmer Rouge regime (1975-1978). Based on reports of the Department of Forestry and Wildlife (DFW) of Cambodia, the forest management of F Com-

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Table 1 Area of forest by type, and change in area, 1973-1993

Types of forests	1973	1993	Change	Annual Change (%)
	(area in 1,000 ha)			
I -Dryland	11,678.6	10,568.6	−1,110.0	−0.5
Evergreen	6,876.4	4,763.3	−2,113.1	−1.5
Deciduous	4,792.9	4,301.2	−491.7	−0.5
Mixed		*977.3*	*977.3*	
Secondary		*517.0*	*517.0*	
Pine	9.3	9.8	0.5	0.3
II- Edaphic	1,032.5	715.6	−316.9	−1.5
Flooded	937.9	370.7	−567.2	−3.0
Flooded Secondary		*259.8*	*259.8*	
Mangrove	94.6	85.1	−9.5	−0.5
Total	12,711.1	11,284.2	−1,426.9	−0.6

Note: Changes in classification introduced in the 1993 study are indicated *in italics* and account for a portion of the changes suggested in the original classifications.
Source: THE WORLD BANK *et al.* (1996)

pany was analyzed with the aid of various statistical tools.

CAMBODIA-THE COUNTRY AND ITS FORESTS

Covering a total land area of 18 million ha, Cambodia is bordered by Thailand to the north-west, Laos to the north, Vietnam to the south-east and the Gulf of Thailand to the south-west. By 1997, Cambodia had a total population of 10.9 million with an annual growth rate of 2.8%.

Forests covered a total area of 10.59 million ha or 58% of the total land area in 1997 (DFW, 1997). All forests in Cambodia are owned by the national government. However, a forest concession system was introduced to Cambodia in early 1991. By 1997, the government had entered into 28 agreements affecting 6.33 million ha (GLOBAL WITNESS, 1998) of total forest area, of which over 3 million ha were well-stocked commercially operable forests. Two forest types have been recognized in Cambodia-dryland (96%) and edaphic (4%) forests. Dryland forests include evergreen, mixed, deciduous, and secondary forests, while edaphic forests include flooded and mangrove forests. Separate management systems are applied to these forests. Two types of selective cutting system are used in Cambodia: the long system with a 25-30 year cycle, and the short, 12-15 year cycle (OUK, 1997). These systems had been adopted in Cambodia prior to 1970, during times of political stability. The long system is used to manage evergreen and semi-evergreen forests, while the short system is used to manage deciduous forests.

The most up-to-date forest resource information for Cambodia is the 1994 Land Cover Atlas prepared by the Mekong Secretariat, Forest Register 1995 by JAFTA (Japan Forest Technical Association) and the unpublished forest cover map produced by DFW in 1997. Although more recent changes may have occurred and been reported, especially along the borders with Thailand and Vietnam, no data are available to evaluate these reports. The total forest area of 11.3 million ha is divided into 4.8 million ha of evergreen forest, 4.3 million ha of deciduous forest, 1 million ha of mixed forest, 0.5 million ha of secondary forest and 0.7 million ha of edaphic forests (Table 1).

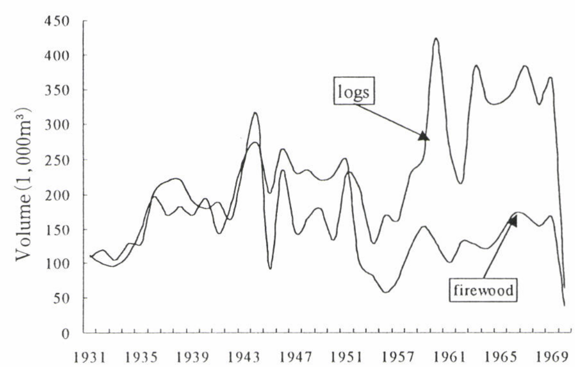

Fig. 1 Forest products in Cambodia (1931-1970)
Source: DFW (1985)

HISTORY OF FOREST MANAGEMENT IN CAMBODIA

On the basis of inscriptions on ancient sculptures found in Cambodia, it is believed that forest institutions existed in Cambodia before the year 639, headed by Khlong Meprey (forest chief). The state of Cambodia has existed since prehistorical times. Cambodians built a famous temple known as Angkor Wat between the 9th and 11th centuries. Subsequently, Cambodia was colonised by France from 1863 to 1953, during which period the Ministry of Forests was established in 1898 (DFW, 1985). The first forest code of practices was established in 1903, and was subsequently revised in 1913, 1916, 1921 and 1930 to make it more adaptable to different locations. The area of forest increased from 10 million ha in 1898 to 13.32 million ha in 1965 (KIMPHAT *et al.*, 1998). However, it declined to 12.71 million ha in 1973 as a result of the Vietnam War (1965-1975). Domestic log production increased from 108,900 m^3 in 1931 to 363,100 m^3 in 1969, but dropped to 63,900 m^3 in 1970, the year when civil war started in Cambodia (Fig. 1).

Forest cover declined further from 12.71 million ha in 1973 to 10.59 million ha in 1997-a loss of more than two million ha. The underlying causes of deforestation in Cambodia include war (Vietnam War 1965-1975, Khmer Rouge Regime 1975-1978, Communism Regime 1979-1989), over-exploitation since 1970 as a result of these wars and political instability, fast growing population, illegal logging and unworkable public administration (KIMPHAT *et al.*, 1999).

TREE CLASSIFICATION

Based on durability and potential utilization, tree species are economically classified into 4 grades (Law Decree No. 050) - Luxury, Grades I, II and III. In addition there are a number of tree species which have been temporarily classified into another class pending evaluation of their potential uses (MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, 1985).

Luxury Grade: The wood is very durable and is used for long-term construction material. In the past and present, villagers have been using these trees for construction of houses, especially for newly married families. Unregulated cutting has caused the gradual loss of some species in this grade. Therefore, extraction of trees in this grade is strictly prohibited.

Grade I and Grade II: The wood is durable. These grades are dominated by *Dipterocarp* trees. They are subject to commercial exploitation.

Grade III: The trees are non-commercial. Trees in this grade are mainly used for fuelwood.

Other: The potential utilization of these tree species has not yet been studied.

CAMBODIA'S SILVICULTURAL TREATMENT SYSTEM

Selective Cutting Cycle of of 25-30 Years

This system or "Under Selective Management System" is applied mainly to dense evergreen and semi-evergreen forest, which are dominated by *Dipterocarp* species. The average growing stock of all trees with diameter greater than 10 cm at breast height in Cambodia's evergreen forest is 230 m^3/ha with a mean growth rate of 0.33 m^3/ha/year (ASHWEL, 1993) (Table 2). The forest harvesting regime is planned on the basis of pre-felling inventory data. Only 30% of the growing stock (of all merchantable trees) that fall within the allowable diameter limits (DBH $\geq$45 cm) may be extracted (Law Decree No.049). The remaining 70% of stands are left as mother trees, which will, in turn, produce seeds and seedlings for natural regeneration. These residual trees function also as shelter for young trees, and they will be extracted in the next felling cycle. This old management system is being put to use in the management of all forest concessions in Cambodia.

Note: [a] in Table 2 and Table 3 derived from equation (1) below:

$$s = [(1+P)^L - 1] \times 100/(1+P)^L \quad (1)$$

where,
s : selective cutting rate as percentage of growing stock
L : cutting cycle in years
P : annual growth rate as percentage of growing stock

Selective Cutting Cycle of 12-15 Years

Table 2 Growth and sustainable cutting rates of Cambodia's evergreen forest

Growth class	Growth rate (m^3/ha/year)	Sustainable cutting rate at 25 years (%)[a]
Slow	0.21	2.25
Fast	0.67	6.98
Average	0.33	3.44

Note: Average growing stock is 230 m^3/ha
Source: ASHWEL (1993) and THE WORLD BANK *et al.* (1996)

Table 3 Growth and sustainable cutting rates of Cambodia's deciduous forest

Growth class	Growth rate (m^3/ha/year)	Sustainable cutting rate at 12 years (%)[a]
Slow	0.08	1.58
Fast	0.34	6.59
Average	0.19	3.76

Note: Average growing stock is 60 m^3/ha
Source: ASHWEL (1993) and THE WORLD BANK *et al.* (1996)

This system is applied to dry deciduous forests with the major deciduous *Dipterocarp* species. *Dipterocarpus obtusifolius* (Tbeng), *Dipt. intricatus* (Trach), *Dipt. tuberculatus* (Khlong), *Shorea obtusa* (Pchek) and *Terminalia tomentosa* (Chlik) of Combretaceae are the dominant species in this forest type. The average growing stock is 60 m^3/ha with an average growth rate of 0.17 m^3/ha/year (Table 3). This forest type usually generates by coppice. The management objective is to extract fuelwood and poles for local needs. Its felling cycle is set between 12 and 15 years. Because of political instability further information is unobtainable.

FOREST MANAGEMENT OF F COMPANY

Location and Forest Area

F Company was granted two forest concessions in 1995, one of which located in the coastal area (DFW 1996). This concession has been divided into 25 annual coupes. The management of coupe No. 1 has been analyzed. This coupe is covered mainly by evergreen forest. It has been under anarchic logging for 4 years (1991-1995).

Inventory System and Growing Stock

The company conducted a pre-harvesting inventory on its annual harvesting coupe, which covers a total area of more than 15,000 ha. Inventory intensity was 5% of the total coupe area or approximately 850 sample plots. All plots were 100 m × 100 m in size, systematically chosen on a rectangular basis of 0.5 km on the base line and 0.4 km on the transect line.

The result of the pre-felling inventory indicates that the volume of all trees with diameter greater than 10 cm is 82 m^3/ha on average-approximately one-third that of virgin evergreen forest which averages 230 m^3/ha, with a density of 298 trees/ha. This clearly shows that this coupe has been and is being over-exploited. The detailed data shows that Luxury Grade trees have an average density of 11 trees/ha and volume of 1.8 m^3/ha, compared to 23 trees/ha and 4.8 m^3/ha for Grade I (Table 4). Table 4 also shows that the remaining trees are mostly small in diameter and volume.

Over-exploitation

One of the most crucial considerations for forest management and investment is sustainable cutting intensity or allowable cut. For a level of harvest forest to be sustainable, each harvest must be limited to the accumulated growth since the last harvest and must leave the stand in a condition to support a resumption of growth at least at the same rate. In the selective cutting systems applied in Cambodian forests, harvesting intensity is expressed in terms of percentage of the standing merchantable volume to be removed. Forest growth in Cambodia has been estimated to be in the order of only 0.3 m^3/ha/year for mixed and evergreen forests. Applied to a cutting cycle of 25 years (current management system), this has been used to establish a harvest limit of 7.5 m^3/ha or approximately 30% of total merchantable volume.

According to Table 4, the total volume of all trees greater than 45 cm DBH is 32.52 m^3/ha (derived from 16.83 + 15.69). Because trees of Luxury Grade are not included in harvest, and trees in Grade III and Other are not subject to cutting due to their unmarketability, only trees

Table 4 Average tree density and volume per hectare by diameter class of F Company's forest

Dia.	Luxury		Grade I		Grade II		Grade III		Others		Total	
Class	Vol.	Den.	Vol.	Den.	Vol.	Den.	Vol.	Den.	Vol.	Den.	Vol.	Den.
10-29	1.13 (3%)	10.3 (4%)	2.37 (8%)	19.2 (8%)	14.25 (43%)	84.5 (34%)	8.12 (25%)	68.6 (28%)	6.93 (21%)	62.9 (26%)	32.80 (100%)	245.5 (100%)
30-44	0.25 (1%)	0.6 (2%)	1.26 (7%)	2.6 (8%)	7.88 (43%)	11.8 (38%)	4.26 (23%)	8.5 (28%)	4.80 (26%)	7.3 (24%)	18.45 (100%)	30.8 (100%)
45-59	0.25 (1%)	0.3 (2%)	0.63 (4%)	0.6 (4%)	7.76 (46%)	6.4 (42%)	4.52 (27%)	4.8 (31%)	3.67 (22%)	3.3 (21%)	16.83 (100%)	15.4 (100%)
>60	0.14 (1%)	0.1 (1%)	0.51 (4%)	0.3 (4%)	9.14 (65%)	4.3 (62%)	1.83 (13%)	0.8 (12%)	2.43 (17%)	1.4 (21%)	15.69 (100%)	6.7 (100%)
Total	1.77 (2%)	11.3 (4%)	4.77 (6%)	22.7 (8%)	39.03 (47%)	107.0 (36%)	18.73 (23%)	82.7 (28%)	17.83 (21%)	74.2 (25%)	82.13 (100%)	298.4 (100%)

Note: Vol. (volume) in m^3/ha, Den. (density) in trees/ha, Dia. (diameter) class in cm.

of Grades I and II (18.04 m^3) can be commercially logged (Table 4). Over the inventoried area of 850 ha, about 6,243.69 m^3 of 8 merchantable tree species with diameter greater than 45 cm have been recorded and are to be extracted. On the basis of the silvicultural treatment principle, only 30% of the growing stock of merchantable trees that fall within the diameter limit for harvesting is available for harvest. Thus, the volume (allowable cut) to be extracted should be 5.41 m^3/ha (derived from 0.63 + 0.51 + 7.76 + 9.14 multiplied by 0.3, of Table 4). F company proposed to cut 30% of merchantable trees with DBH greater than 45 cm and 50% of trees with diameter greater than 59 cm, so the harvest volume would be increased to 7.34 m^3/ha (derived from 2.52 + 4.82 of Table 5).

Using equation (1) above, and based on Table 4, F's mean growing stock is 82.13 m^3/ha, and F's actual cut on a 25-year cutting cycle is 7.34 m^3/ha or 8.94% of the total growing stock. This rate is 5.5 percentage points higher than the average sustainable cutting rate of Cambodia's evergreen forest (Fig. 2). This practice is unacceptable and will cause forest degradation. Enrichment planting is required.

Table 5 Volume of merchantable trees by diameter class in F Company's forest on an inventoried area of 850 ha

Tree Species DBH class		45-59 cm		Greater than 60 cm		Total	
Code	Scientific Name	Total (m^3)	Average (m^3/ha)	Total (m^3)	Average (m^3/ha)	Total (m^3)	Average (m^3/ha)
Class I							
KKMS	*Hopea spp.*	189.01	0.22	110.41	0.13	299.42	0.35
DCSP	*Tarrietia javanica*	322.53	0.38	289.93	0.34	612.46	0.72
WYNG	*Chukrsia tabularis*	24.47	0.03	31.51	0.04	55.98	0.07
Sub-total		536.01	0.63	431.85	0.51	967.73	1.14
Class II							
PHDK	*Anisoptera glabra*	1,912.02	2.25	2,065.87	2.43	3,977.73	4.68
CHTR	*Dipterocarpus spp.*	2,647.22	3.11	3,091.43	3.64	5,738.65	6.75
KKKS	*Hopea pierrei*	176.34	0.21	247.59	0.29	423.93	0.50
KKPN	*Shorea hypochra*	1,337.17	1.57	1,702.32	2.00	3,039.49	3.58
LMBI	*Shorea sp.*	525.67	0.62	667.67	0.78	1,193.34	1.40
Sub-total		6,598.42	7.76	7,774.88	9.14	14,373.30	16.91
Grand total		7,134.43	8.39	8,206.73	9.65	15,341.03	18.05
Company's actual cut		2,140.33	2.52	4,103.36	4.82	6,243.69	7.34
Sustainable cut		2,140.33	2.52	2,462.02	2.89	4,602.35	5.41

Note: The diameter limits for harvesting are 45 cm for KKMS, DCSP, KKKS, KKPN, LMBI and PHDK, and 60 cm for CHTR and WYNG.

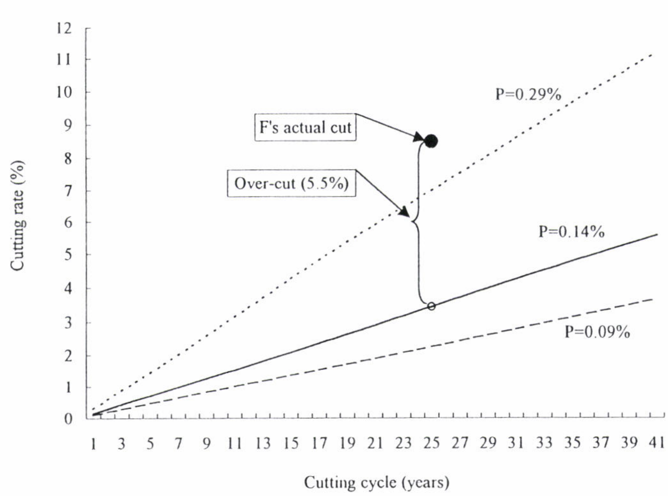

Fig. 2 Relationship between cutting rate and cutting cycle of Cambodia's evergreen forest

DISCUSSION AND CONCLUSION

Forest management in Cambodia is strongly influenced by regional dynamics of wood demand and supply. Rapid deforestation in major wood exporting countries in south east Asia, such as Philippines, Thailand, Vietnam and Malaysia has forced Cambodia to move from being previously a minor wood exporter to becoming a major wood exporter to the region in recent years. Shortage of human resources, financial constraints, and government instability, especially along the borders with Thailand and Vietnam, has encouraged illegal loggers from inside and outside the countries to over-exploit forests without concern for the future of Cambodian people, whose economic development depends mainly on forest resources. The over-exploitation (5.5%) of forest products being practiced by F Company causes the forest degradation, and if the remaining forest is not properly protected and managed, deforestation is likely to occur. Until recently, professional foresters have been concerned with the management of forests for the sustained yield of wood production alone. While based on sustainability principles, it is not a long-term sustainability. Thus, forest managers should formulate appropriate methodological guidelines for assessing long-term sustainability. Besides the exploitation of commercial tree species, the company should also extract the trees of the third and other grades for fuelwood production as done prior to 1970 (DFW 1985), because approximately 92% of Cambodian population still depend mainly on fuelwood for daily cooking energy and warmth. This practice would reduce the clearing of wood inside forest concessions by nearby villagers for fuelwood.

The results of this study indicate that the number of residual trees with diameter less than 45 cm in all grades in the forest remains high (Fig. 3). Under legal management this forest can provide more wood and environmental services for present and future needs. The Luxury Grade, very distinct species, and Grade I - the commercial species -remain a very small proportion of the remaining trees, which makes enrichment planting necessary.

The study concluded that over a period of 25-30 years, the trees with diameter less than 40 cm should reach minimum diameter for harvesting. Thus the recommendation is that all trees with diameter greater than 40 cm can be extracted as long as they meet the silvicultural guidelines. While further study of growth rates of specific forest areas is strongly recommended, more data collection, storage and analysis is needed to evaluate whether or not the present forest management practices are sustainable.

While cooperation with neighboring countries is required, strong enforcement mechanisms for current forest monitoring and control are needed to stop illegal logging, to prevent over-exploitation of forest products and to properly manage the remaining trees. The participation of local, national and international communities is required to provide financial and technical assistance the management of Cambodia's forests on a sustainable basis.

Above all, while establishing a national forest planning system, the government should provide a long-term commitment to research infrastructure in terms of fieldwork facilitation, documents and technical and financial assistance. To effectively manage the forest on a sustainable basis, forest certification schemes such as FSC, and ISO 9000 and 14001 should be introduced.

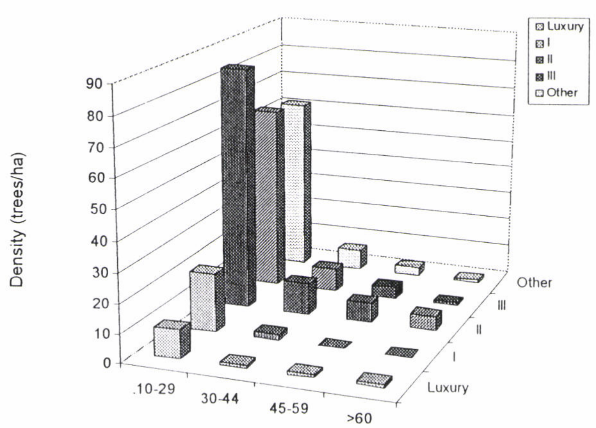

Fig. 3 Relationship between tree density and diameter class by grade for F Company's evergreen forest harvesting

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Short communication

Statistical Analysis of the Relationship between Upper- and Mean-Tree Heights using Discriminant Analysis Method

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ABSTRACT

Even-aged pure forest stands of Japanese cedar (*Cryptomeria japonica* D. Don) and Japanese cypress (*Chamaecyparis obtusa* Endl.) were statistically stratified into upper and lower strata using the discriminant analysis method. The mean height of the stratified upper trees was defined as the "upper tree height (H_u)", and the relationship between H_u and mean tree height (H_m) was analyzed. A strongly positive correlation was observed between H_u and H_m, and well-fitting empirical equations for H_m and H_u were derived for Japanese cedar stands as: $H_u=1.091H_m$ ($r=0.979$) and for Japanese cypress stands as: $H_u=1.056H_m$ ($r=0.997$). The upper strata in Japanese cedar and Japanese cypress stands were considered to be composed of 67% and 58% of the total number of trees, respectively. These equations or component ratios could be used in estimating upper tree height.

Keyword: discriminant analysis method, even-aged pure forest stand, mean tree height, upper tree height

INTRODUCTION

The stand density control diagram (Ando, 1968) has been widely used in the determination of planting density and the planning of thinning operations for even-aged pure coniferous forest stands. Using this diagram, prospective stand characteristics such as the stand volume, total basal area, and mean diameter can be estimated based on the dominant height (H_d) and stand density (Ando, 1968).

As one problem of this diagram, Morita (1984; 1985) pointed out that the definition of the term "dominant height" was uncertain and the relationship between H_d and mean tree height (H_m) has not been described. Although the dominant height is generally defined as the mean height of the dominant trees that comprise the upper canopy (Osumi *et al.*, 1991), it is considered to be difficult to select the dominant trees objectively. On that basis, Morita (1985) proposed empirical equations for H_d and H_m for Japanese cedar (*Cryptomeria japonica* D. Don) stands as:

$$H_d=0.308+1.099H_m \quad (r=0.996) \qquad (1)$$

and for Japanese cypress (*Chamaecyparis obtusa* Endl.) stands as:

$$H_d=0.237+1.111H_m \quad (r=0.986) \qquad (2)$$

However, Morita (1985) did not mention how these equations were derived, and the definition of the dominant height remained uncertain.

On the other hand, Inoue *et al.* (1997; 1998) applied the discriminant analysis method (DAM), which was originally proposed for image analysis by Otsu (1979; 1980), to the analysis of forest stratification. Using DAM, a forest stand can be statistically stratified into several strata and the number of strata to be stratified can be arbitrarily selected (Inoue *et al.*, 1998). Since an even-aged pure forest stand is often stratified into upper and lower strata (e.g. Tanaka, 1983), first, even-aged pure forest stands of Japanese cedar and Japanese cypress are statistically stratified into two strata using DAM. Next, the mean height of the stratified upper trees is defined as the "upper tree height (H_u)", and then, the relationship between H_u and H_m is statistically analyzed.

MATERIALS AND METHODS

Study Area

This study was conducted in 22 Japanese cedar and 17 Japanese cypress even-aged pure forest stands in the Kyu-

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shu University Forest in Fukuoka, Japan. Square plots of 0.02 ha were set up for each stand, and the height of all living trees was measured. All plots were measured twice with a 3-year interval. A general description of the plots is shown in Table 1.

Data Analysis

First, each plot was stratified into upper and lower strata using DAM. The DAM is simply explained as follows (Inoue *et al.*, 1997; 1998): Stratifying a forest stand into two strata requires the determination of a threshold on the tree height histogram. The threshold value (k) can be determined based on the discriminant criterion. Let the tree heights of a forest stand be represented in L tree height classes. The number of trees at class i is denoted by n_i, and the total number of trees in the stand is given by N. Then, the forest stand can be stratified at the threshold that gives the maximum between-class variance $\sigma_B^2(k)$:

$$\sigma_B^2(k) = P_u(H_u - H_m)^2 + P_l(H_l - H_m)^2 \quad (3)$$

This requires the following statistics,

$$P_i = n_i/N \quad (4)$$

$$P_l = \sum_{i=1}^{k} p_i \quad (5)$$

$$P_u = \sum_{i=k+1}^{L} p_i \quad (6)$$

$$H_l = \sum_{i=1}^{k} ip_i/P_l \quad (7)$$

$$H_u = \sum_{i=k+1}^{L} ip_i/P_u \quad (8)$$

$$H_m = \sum_{i=1}^{L} ip_i \quad (9)$$

where P_l and P_u are the component ratios of the number of lower and upper trees, respectively, and H_l is the lower tree height.

Next, the following two regression lines are fitted to the relationship between H_u and H_m,

$$H_u = a_1 H_m + b \quad (10)$$

$$H_u = a_2 H_m \quad (11)$$

where a_1, a_2, and b are constants for each species. The former (line 1) is the same form as the equations proposed by Morita (1985) and the latter (line 2) is a modification of line 1 that intersects the origin. Lines of the same form are also fitted to the relationship between H_l and H_m.

In general, the goodness of fit of a regression line increases with the number of constants in the line. Then, the goodness of fit of two lines is compared using Akaike's

Table 1 General description of the plots

Species	Number of samples	Mean tree height (m)	Coefficient of variation of tree height (%)	Stand density (trees/ha)
Japanese cedar	44	18.3 8.1~38.0	14.3 2.1~25.2	1,178 200~4,400
Japanese cypress	34	16.5 6.0~25.1	9.2 3.6~24.0	1,469 400~4,950

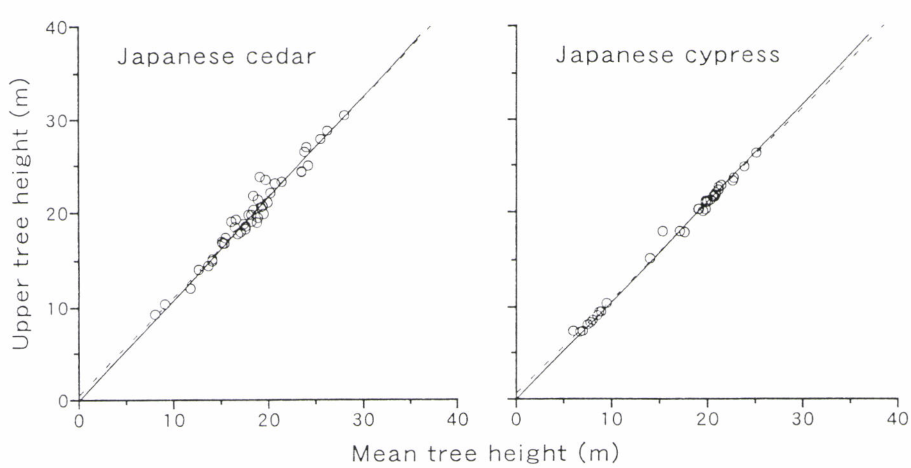

Fig. 1 Relationship between upper and mean tree heights
Note: The broken and solid lines show the regression lines 1 and 2, respectively.

information criterion (AIC) (AKAIKE, 1974),

$$\text{AIC} = M\log(S/M) + 2m \quad (12)$$

where M is the number in the sample, S is the sum of the squares of residuals, and m is the number of constants in the regression line. The regression line having the smaller AIC value is chosen as the better one. A significant difference in the AIC values between two lines can be evaluated by comparing it with the variability of a chi-square variable having the degree of freedom equal to the difference of these two lines. Thus, if the difference is more than 2, we can take the line having the smaller AIC value as significantly more appropriate than the other line.

RESULTS AND DISCUSSION

Relationship between Upper-and Mean-Tree Heights

Fig. 1 shows the relationship between upper tree height (H_u) and mean tree height (H_m). A strongly positive correlation was observed between H_u and H_m for both species ($p<0.01$). This suggests that H_u derived by the use of DAM can be estimated from H_m.

The constants and AIC values of two regression lines are shown in Table 2. The AIC value of line 2 was significantly smaller than the value of line 1 for both species. This shows that line 2 is better fitted to the relationship between H_u and H_m than line 1. From this, it can be considered that the relationship between H_u derived by the use of DAM and H_m can be expressed by the empirical equations for Japanese cedar stands as:

$$H_u = 1.091H_m \quad (r=0.979) \quad (13)$$

and for Japanese cypress stands as:

$$H_u = 1.056H_m \quad (r=0.997) \quad (14)$$

Using these derived equations, the upper tree height can be estimated from mean tree height.

Table 2 Constants and AIC values of regression lines between upper and mean tree heights

Species	Regression line 1			Regression line 2	
	a_1	b	AIC	a_2	AIC
Japanese cedar	1.067	0.461	14.078	1.091	−0.917
Japanese cypress	1.024	0.600	10.861	1.056	−20.928

Table 3 Constants and AIC values of regression lines between lower and mean tree heights

Species	Regression line 1			Regression line 2	
	a_1	b	AIC	a_2	AIC
Japanese cedar	0.848	−0.613	34.031	0.816	32.104
Japanese cypress	0.987	−1.183	3.632	0.924	3.889

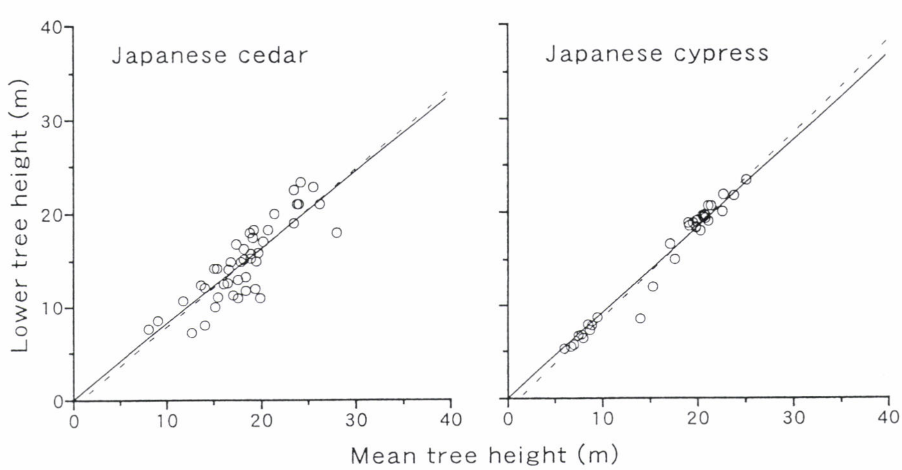

Fig. 2 Relationship between lower and mean tree heights
Note: The lines are the same as those shown in Fig.1.

Relationship between Lower- and Mean-Tree Heights

As shown in Fig. 2, a positive correlation was also observed between H_l and H_m for both species ($p<0.01$). The correlation coefficient was smaller for Japanese cedar stands than Japanese cypress stands. This is due to the difference in the variations in tree height, that is, the coefficient of variation of tree height within stands was greater in Japanese cedar than in Japanese cypress (see Table 1).

The constants and AIC values of the two lines are shown in Table 3. Since no significant difference in the AIC values was observed for either species, it could not be concluded which line was better fitted to the relationship between H_l and H_m. Then, in order to unify the form of the regression line, hereafter, the equations of the relationship between H_l and H_m were used for Japanese cedar stands as:

$$H_l = 0.816H_m \quad (r=0.849) \tag{15}$$

and for Japanese cypress stands as:

$$H_l = 0.924H_m \quad (r=0.986) \tag{16}$$

Component Ratio of the Number of Upper- and Lower-Trees

By mathematical definition, the following relations always hold true:

$$H_m = P_l H_l + P_u H_u \tag{17}$$

$$P_l + P_u = 1 \tag{18}$$

Substituting eqs. 13 and 15 into eq. 17 and dividing both sides of this into H_m, we obtain,

$$0.816P_l + 1.091P_u = 1 \tag{19}$$

Solving the simultaneous equations 18 and 19, we obtain the following solution:

$$P_l = 0.331, \quad P_u = 0.669 \tag{20}$$

This shows that the number of lower-and upper-trees for Japanese cedar are in the ratio 0.331: 0.669. Similarly, the component ratio for Japanese cypress is 0.424: 0.576. From this, it can be said that the upper strata stratified by the use of DAM in Japanese cedar and Japanese cypress stands are composed of 67% and 58% of the total number of trees, respectively. The upper tree height can be estimated by the use not only of eqs. 13 and 14 but also of these component ratios.

CONCLUSION

In this paper, the relationship between upper tree height (H_u) and mean tree height (H_m) for even-aged pure forest stands of Japanese cedar and Japanese cypress was analyzed. The derived empirical equations for H_u and H_m are different from the equations for H_d and H_m proposed by Morita (1985), from the viewpoint that the definition of the term "upper tree height" is clear. In a later paper, the relationships between H_u derived by the use of discriminant analysis method and stand characteristics will also be statistically analyzed, and a new stand density control diagram will be developed based on these relationships.

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Short communication

A New Method for Analyzing Forest Stratification based on Discriminant Criteria (II) —Comparison with a Method based on Symmetric Type Difference Diagrams—

Akio Inoue*

ABSTRACT

The discriminant analysis method (DAM), which is a method for analyzing forest stratification, was qualitatively compared with a method using symmetric type difference diagrams (SDM) by applying both methods to four types of actual forest stands. The number of strata determined by DAM and SDM were different. Using SDM, cases of forest stands that could not be successfully stratified into several strata were observed, and the number of strata and boundaries between the strata could not be objectively determined. On the other hand, forest stands could be stratified into several strata not subjectively but objectively with DAM. However, it could not be judged with DAM whether a forest stand is composed of one stratum or two strata, whereas this was possible with SDM. From these results, it cannot be concluded which method is superior to the other since they have different advantages and disadvantages. It is therefore considered important to choose the appropriate method or to combine the two methods depending on the purpose of analysis.

Keyword: discriminant analysis method, forest stratification, qualitative comparison, symmetric type difference diagram

INTRODUCTION

A forest stand is made up of several vertical strata of various tree sizes. Generally, this type of stratiform structure of a forest stand is called "forest stratification". It reflects the biological characteristics of tree species such as their regeneration and growth pattern etc. Hence, the analysis of forest stratification helps to clarify the dynamic aspects of a forest stand (Ninomiya and Ogino 1986).

In order to analyze forest stratification, various methods have been proposed. Ogawa *et al.* (1965) developed the crown depth diagram, which is based on the relationship between tree height and clear bole length. Hozumi (1975) proposed a numerical method using the $M-w$ diagram, which is based on tree weight distribution. Yamakura (1987) developed a numerical method using the symmetric type difference diagram, which is based on tree height distribution. Okano and Aragami (1999) also proposed a method using the $H-h$ diagram, which is an application of the $M-w$ diagram to tree height distribution. These are graphical methods in which the points plotted on the diagram can be visually discerned by a few segmental lines or groups, each of which corresponds to a stratum of the forest stand.

On the other hand, Inoue *et al.* (1997; 1998) newly applied the discriminant analysis method (DAM), which was originally proposed for image analysis by Otsu (1979; 1980), to the analysis of forest stratification. The DAM is based on tree height data, and its advantages are as follows: (Inoue *et al.*, 1998): 1) A forest stand can be stratified into several strata not visually but statistically; 2) The number of strata to be stratified can be arbitrarily selected; 3) The optimal number of strata to be stratified can be estimated; 4) The degree of stratification can be quantified. These features make DAM one of the most effective

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methods for analyzing forest stratification.

In order to evaluate the validity of DAM, it is necessary to compare it with those previously mentioned graphical methods. In this paper, DAM is qualitatively compared with the method using symmetric type difference diagrams (YAMAKURA, 1987; SDM), which, like DAM, requires only the tree height data, by applying both methods to four types of actual forest stands.

ANALYSIS METHODS

Discriminant Analysis Method

In this chapter, the method for analyzing forest stratification using DAM is explained according to INOUE *et al.* (1997; 1998) and OTSU (1979; 1980).

In order to stratify a forest stand into several strata, the determination of the "threshold(s)" between strata is required. For example, if a forest stand is stratified into M strata, $(M-1)$ threshold(s) are required. A schematic diagram of the stratification method is shown in Fig. 1. The threshold(s) can be determined using DAM. Let the trees of a forest stand be represented in L tree height classes by:

$$S = \{1, 2, \cdots, L\} \tag{1}$$

The number of trees at height class i is denoted by n_i and the total number of trees by $N = n_1 + n_2 + \cdots + n_L$. In order to simplify the discussion, the tree height histogram is normalized:

$$p_i = n_i / N \ (i \in S,\ p_i \geqq 0,\ \sum_{i=1}^{L} p_i = 1) \tag{2}$$

Now, suppose that we stratify the forest stand into M strata S_j by $(M-1)$ threshold(s) at class k_j: $1 \leqq k_1 < k_2 < \cdots < k_{M-1} < L$, where $k_0 = 0$ and $k_M = L$:

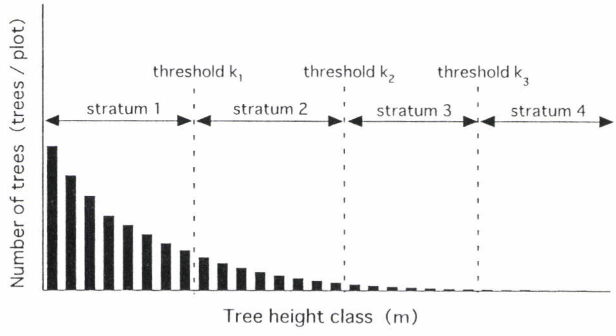

Fig. 1 Schematic diagram of the discriminant analysis method

$$S_j = [k_{j-1}+1, \cdots, k_j] \quad (j = 1, \cdots, M) \tag{3}$$

Then, the probability of occurrence of the j-th stratum ω_j and the mean tree height class of the j-th stratum μ_j, respectively, are given by:

$$\omega_j = \Pr(S_j) = \sum_{i \in S_j} p_i = \omega(k_j) - \omega(k_{j-1}) \tag{4}$$

$$\mu_j = \sum_{i \in S_j} i \Pr(i|S_j) = \sum_{i \in S_j} i p_i / \omega_j$$

$$= \{\mu(k_j) - \mu(k_{j-1})\} / \{\omega(k_j) - \omega(k_{j-1})\} \tag{5}$$

where

$$\omega(k_j) = \sum_{i=1}^{k_j} i p_i, \ (\omega(0) = 0, \ \omega(L) = 1) \tag{6}$$

$$\mu(k_j) = \sum_{i=1}^{k_j} i p_i \ (\mu(0) = 0) \tag{7}$$

These are the zero- and the first-order cumulative moments of the histogram up to the k_j-th class, respectively, and μ_T is the total mean tree height class of the stand:

$$\mu_T = \mu(L) = \sum_{i=1}^{L} i p_i \tag{8}$$

We can easily verify the following relationships for any choice of k_j:

$$\sum_{j=1}^{M} \omega_j \mu_j = \mu_T, \ \sum_{j=1}^{M} \omega_j = 1 \tag{9}$$

The variance of each stratum is given by:

$$\sigma_j^2 = \sum_{i \in S_j} (i - \mu_j)^2 \Pr(i|S_j) = \sum_{i \in S_j} (i - \mu_j)^2 p_i / \omega_j \tag{10}$$

This requires a second-order cumulative moment.

In order to evaluate the goodness of the threshold k_j, we shall introduce the following discriminant criterion measures used in discriminant analysis:

$$\lambda = \sigma_B^2 / \sigma_W^2, \ \kappa = \sigma_T^2 / \sigma_W^2, \ \eta = \sigma_B^2 / \sigma_T^2 \tag{11}$$

where

$$\sigma_W^2 = \sum_{j=1}^{M} \omega_j \sigma_j^2 \tag{12}$$

$$\sigma_B^2 = \sum_{j=1}^{M} \omega_j (\mu_j - \mu_T)^2 \tag{13}$$

$$\sigma_T^2 = \sum_{j=1}^{L} p_i (i - \mu_T)^2 \tag{14}$$

are the within-class variance, the between-class variance and the total variance of tree height class, respectively. Then, our problem is reduced to an optimization problem which requires us to search for the thresholds k_j that maximize one of the object equations in eq. 11. This approach is based on the conjecture that well-thresholded strata would be well stratified and, conversely, that the best thresholds would be those giving the best separation of strata.

However, the discriminant criteria maximizing λ, κ and η, respectively, for k_j are equivalent to one another; e. g., $\kappa=\lambda+1$ and $\eta=\lambda/(\lambda+1)$ in terms of λ, since the following basic relation always holds:

$$\sigma_T^2=\sigma_W^2+\sigma_B^2 \tag{15}$$

It is noticed that σ_W^2 and σ_B^2 are functions of thresholds, whereas σ_T^2 is independent of thresholds. It is also noted that σ_W^2 is based on the second-order statistics, while σ_B^2 is based on the first-order statistics. Hence, η is the simplest measure with respect to k_j. Thus we adopt η as the criterion measure to evaluate the goodness of the thresholds.

The optimal thresholds k_j^* that maximize η, or equivalently maximize σ_B^2, are selected in the following sequential search by using the simple cumulative quantities given by eqs. 6 and 7, or explicitly using eqs. 4 and 5:

$$\eta\ (k_j)=\sigma_B^2(k_j)/\sigma_T^2 \tag{16}$$

$$\sigma_B^2\ (k_j)=\sum_{j=1}^{M}\omega_j(\mu_j-\mu_T)^2$$

$$=\sum_{j=1}^{M}\omega_j\mu_j^2-\mu_T^2 \tag{17}$$

Hence, the optimal thresholds k_j^* are determined:

$$\sigma_B^2(k_j^*)=\max_{1\leq k_j<L}\sigma_B^2\ (k_j) \tag{18}$$

From this problem, the range of k_j over which the maximum is sought can be restricted to:

$$S^*=\{k_j;\prod_{j=1}^{M}\omega_j>0 \text{ or } 0<\omega(k_j)<1\} \tag{19}$$

We shall call this the effective range of the tree height histogram. From the definition in eq. 13, the criterion measure σ_B^2 (or η) takes a minimum value of zero for such k_j as $k_j\in S-S^*=\{k_j;\ \omega(k_j)=0 \text{ or } 1\}$ and takes a positive and bounded value for $k_j\in S^*$. Hence, it is obvious that the maximum always exists.

Since η is the ratio of σ_B^2 to σ_T^2, η is within the following range:

$$0\leqq\eta\leqq1 \tag{20}$$

η is a measure to evaluate the separability of strata (degree of stratification), which increases with the increase in the degree of separation between each stratum. The lower bound value is attainable only by the stand composed of a single tree height class, and the upper bound value is also attainable only by M tree height classes.

The optimal number of strata to be stratified can be estimated using DAM. Let η_M denote the variance ratio when the stand is stratified into M strata. Since η_M is the ratio of σ_B^2 to σ_T^2, η_M has a natural bias, such that η_M increases with the increase in the number of strata to be stratified M:

$$\eta_2<\eta_3<\cdots<\eta_L=1 \tag{21}$$

In order to obtain a significant measure for comparison, this natural bias must be removed. If we consider the uniform tree height histogram and assume $M\ll L$, the optimal thresholds are determined at the points dividing the range of tree height classes L into M equal parts. In this case, it is obvious that the variance ratio η_M^* can be evaluated by the following equation:

$$\eta_M^*=(M^2-1)/M^2 \tag{22}$$

We shall introduce the Q_M value as an example of the value that will remove the natural bias:

$$Q_M=\log\ \{\eta_M/(1-\eta_M)\}-\log\ \{\eta_M{}^*/(1-\eta_M{}^*)\}$$

$$=\log\ \{\eta_M/(1-\eta_M)\}-\log(M^2-1) \tag{23}$$

The upper bound value, lower bound value and eq. 22 lead to the Q_M value $+\infty$, $-\infty$ and zero, respectively. Hence, Q_M is the unbiased value for stratified M strata, and the optimal number of strata to be stratified M^* can be estimated:

$$Q(M^*)=\max_{2\leq M\ll L}Q_M \tag{24}$$

Hozumi (1975) reported that the numbers of strata of various types of forest stands stratified by the $M-w$ diagram range from one to four. Furthermore, the number tends to decrease with the increase in climatically stressed conditions (Hozumi, 1975; Ninomiya and Ogino, 1986; Yamakura, 1987). From these facts, assuming that the maximum number of strata is four, the Q_M values for two, three and four strata are compared.

Symmetric Type Difference Diagram Method

In this chapter, the SDM is explained according to Yamakura (1987). Yamakura (1987) applied a derivative of Pearson's type Ⅶ distribution (Yamakura and Shinozaki 1980; 1983) to the tree height distribution function. This function expresses a truncated distribution and can formulate any statistics, such as the mean and variance of the data, by an explicit algebraic function. Furthermore, this function is very convenient for the analysis of the ordered arrangement of the tree height data. The properties of this function offer a useful approach for the elucidation of forest stratification. The outline of this function is explained as follows:

Denoting individual tree height and its distribution density function in a forest stand as H and $\phi(H)$, respectively. $\phi(H)$ is expressed in the form:

$$\phi(H) = \{\alpha^2(H-H_m)^2+\phi^{-2}(H_m)\}^{-1/2} \tag{25}$$

where H_m, α and $\phi(H_m)$ are coefficients specific to a forest stand. The relationship between H and $\phi(H)$ was empirically derived from the following relation for the rank (ξ) of any tree in an ordered ranking of the tree height, $H(1) \geqq H(2) \geqq \cdots \geqq H(\xi) \geqq \cdots$. The corresponding value of ξ of a forest stand grown on a given land area is,

$$H(\xi) = C_1 e^{-\alpha\xi} - C_2 e^{\alpha\xi} + H_m \tag{26}$$

where C_1 and C_2 are coefficients specific to the forest stand. In eq. 26, the variable ξ corresponds to the cumulative frequency of tree height or empirical distribution function of tree height. Hence, eq. 26 represents an inverse function of the empirical distribution function of H. Here, we define any difference in ξ as τ and denote the heights of the ($\xi+\tau$) -th tree and ($\xi-\tau$) -th tree as $H(\xi+\tau)$ and $H(\xi-\tau)$, respectively. We can derive the following relationship from eq. 26,

$$H(\xi+\tau) + H(\xi-\tau) = a_\tau H(\xi) + b_\tau \tag{27}$$

where

$$a_\tau = e^{-\alpha\xi} + e^{\alpha\xi} \tag{28}$$

$$b_\tau = (2-a_\tau) H_m \tag{29}$$

Eq. 27 was designated as a symmetric type difference equation of the second order (Yamakura and Shinozaki, 1980) and was adopted to clarify the forest stratification.

The diagram showing the relationship between $H(\xi)$ and $H(\xi+\tau)+H(\xi-\tau)$ is tentatively designated as the symmetric type difference diagram, since it corresponds to the finite difference equation of the second order or eq. 27 designated as the symmetric type difference equation of the second order. In drawing the diagram, the available sets of data depend on the finite difference (τ) of ξ and are equal to the mathematical term, $N-2\tau$, where N is the total number of trees in the stand as mentioned above. Furthermore, it is worth mentioning that $H(\xi-\tau) \gg H(\xi+\tau)$, if $\tau \gg 0$. Thus, the ratio of $H(\xi-\tau)$ to the sum of $H(\xi+\tau)$ and $H(\xi-\tau)$ increases with the increase in τ. Hence, the diagram is more sensitive to the changes of large $H(\xi)$ than to the changes of small $H(\xi)$. This property of the diagram is reasonable in the analysis of forest stratification, since large-size trees contribute a large proportion of the biomass, productivity and respiration of a forest stand.

If any forest stand consists of several strata, if the frequency distribution of H in each strata is approximated by the derivative of Pearson's type VII distribution, and if the symmetric type difference diagrams are drawn by using sufficiently large τ values satisfying the following conditions, then the dot arrangement pattern on the diagrams is approximated by linear segmental lines, each of which corresponds to a given stratum, i.e.,

$$\tau \geqq \sum_{j=2}^{J} N^*_j \text{ and } N^*_1 \gg \sum_{j=2}^{J} N^*_j \tag{30}$$

where the subscript j is the identification number of a stratum, J is the maximum value of j, N^*_j is the number of trees in the j-th stratum, and N^*_1 is the number of trees in the lowest stratum. Furthermore, the number of trees in each stratum can be graphically obtained by counting the number of dots aligned on each segment. The use of different τ values is necessary for discerning the strata on the diagrams, since the dot arrangement pattern depends on τ and available τ cannot be estimated before drawing the diagram.

DATA

The DAM and SDM were both applied to the same four forest stands, each of a different type. An outline of these four stands is as follows:

Japanese Cedar Natural Forest Stand on Yakushima Island, Japan

The first stand is a Japanese cedar (*Cryptomeria japonica* D. Don) natural forest on Yakushima, an island off the south coast of Kyushu, Japan's southern most main island (Yoshida and Imanaga, 1990). A plot of 1.0ha (100 m×100m) was set up in the natural forest stand. The tree heights of 1,020 trees in the plot with 4.0cm and more in DBH (diameter at 1.2m height) were measured. According to Yoshida and Imanaga (1990), Japanese cedar occupied the upper stratum and there was no regeneration and ingrowth of Japanese cedar in the stand.

Dry Evergreen Forest Stand in Sakaerat, Thailand

The second stand is a dry evergreen forest stand, in Sakaerat in the northern region of Thailand. Tree heights for this stand were read from a forest profile diagram drawn by Yamakura (1987). According to Yamakura (1987), the plot size was 50m long and 10m wide, and 75 living trees and one dead Hopea ferrea tree were drawn in the diagram. However, only 63 trees were found on the diagram. This difference of 12 trees resulted from either some trees being hidden in the diagram-drawing or from errors in tree-height-reading from the diagram. However, we could not check this difference because of a lack of original data.

Primary Mixed Forest Stand in Moraballi Creek, British Guiana

The third stand is a primary mixed forest stand in Moraballi Creek, British Guiana. Tree height data was also read from a forest profile diagram drawn by DAVIS and RICHARDS (1933). According to DAVIS and RICHARDS (1933), there were 66 living trees in the diagram. However, only 55 trees were found on the diagram.

Japanese Cedar Even-aged Pure Forest Stand, Japan

The fourth is a Japanese cedar 25-year even-aged pure forest stand in the Kyushu University Forest in Fukuoka, Japan. A plot of 0.02ha was set up in the forest stand. The tree height, DBH and branch heights of all Japanese cedar living trees were measured. The mean tree height, DBH and branch height were 8.8m, 14.1cm and 4.9m, respectively, and the stand density was 4,400 trees/ha.

RESULTS AND DISCUSSION

Fig. 2 shows the tree height histogram for the Japanese cedar natural forest stand in Yakushima. It seems

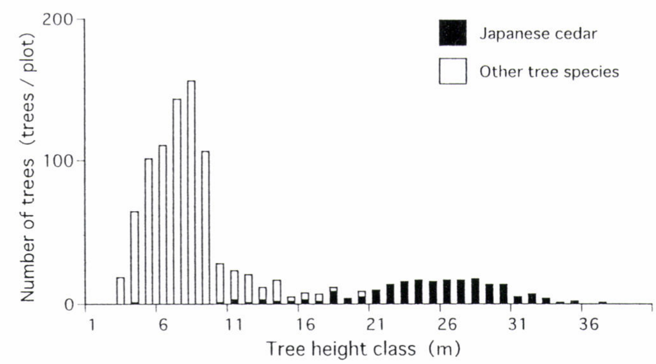

Fig. 2 Tree height histogram for a Japanese cedar natural forest stand on Yakushima, Japan

Table 1 Thresholds, variance ratios and Q_M values for a Japanese cedar natural forest stand determined by DAM

number of strata (M)	thresholds (k_j)	variance ratio (η_M)	Q_M value
2	16	0.852	0.283
3	12,22	0.911	0.107
4	8,16,25	0.944	0.051

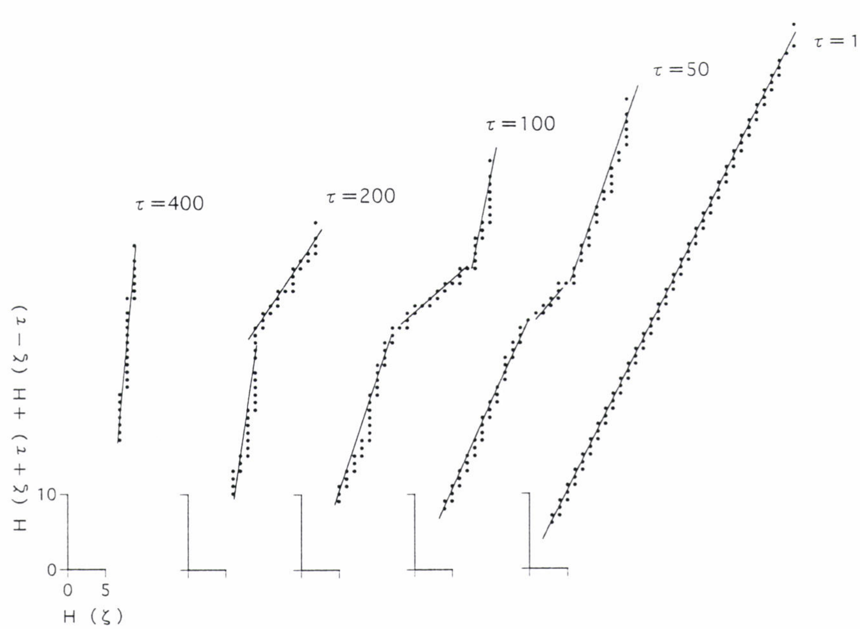

Fig. 3 Some examples of symmetric type difference diagrams for a Japanese cedar natural forest stand on Yakushima, Japan

that this stand is made up of two strata, with upper- and lower-strata composed of Japanese cedar and other tree species, respectively. Table 1 shows the thresholds, variance ratios and Q_M values for the forest stand determined by DAM. It is considered that this stand is made up of two strata, since the Q_M value was maximized when M was two. The first (taller) stratum consisted of trees in the 17 m or taller height classes and the second (lower) stratum of trees in the 16m or lower height classes. The trees in the first stratum were almost all Japanese cedar trees. This finding is consistent with the report of YOSHIDA and IMANAGA (1990).

Fig. 3 shows some examples of symmetric type difference diagrams for the Japanese cedar natural forest stand. When τ was one, the relationship between $H(\xi)$ and $H(\xi+\tau)+H(\xi-\tau)$ and/or symmetric type difference diagram was approximated by a single line. However, the relationships seemed to be approximated by three segmental lines when τ was fifty and one hundred. Although the relationship was discerned by two segmental lines when τ was two hundred, it returned to a single line when τ was four hundred. YAMAKURA (1987) said that the use of sufficiently large τ values are effective in the discernment of segmental lines. However, the result shows that the number

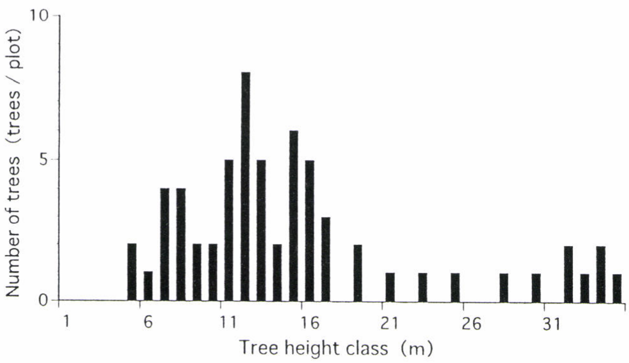

Fig. 4 Tree height histogram for a dry evergreen forest stand in Sakaerat, Thailand
Note: Tree height records were read from the profile diagram drawn by YAMAKURA (1987).

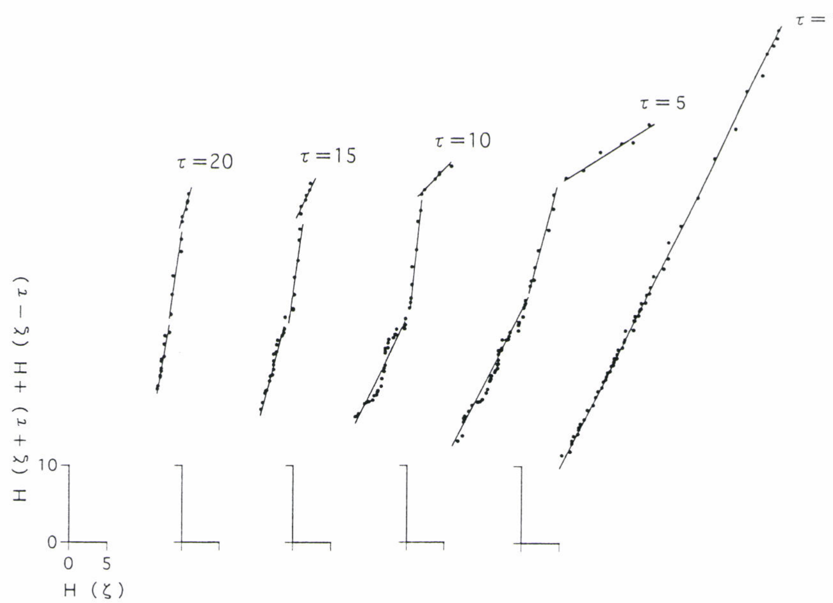

Fig. 5 Some examples of symmetric type difference diagrams for a dry evergreen forest stand in Sakaerat, Thailand

Table 2 Thresholds, variance ratios and Q_M values for a dry evergreen forest stand determined by DAM

number of strata (M)	thresholds (k_j)	variance ratio (η_M)	Q_M value
2	19	0.750	0.000
3	15,25	0.868	−0.085
4	10,15,25	0.937	−0.004

of segmental lines, each of which corresponds to the number of strata, changes with the τ values. From this, it is considered that the number of strata of this stand cannot be objectively determined from these diagrams.

Fig. 4 shows the tree height histogram, and Table 2 shows the thresholds, variance ratios and Q_M values determined by DAM for the dry evergreen forest stands. Since the Q_M value was maximized when M was two, this stand is considered to be composed of two strata with a threshold at the 19m tree height class.

Fig. 5 shows some examples of symmetric type difference diagrams for the dry evergreen forest stand. When τ was five or more, the relationships between $H(\xi)$ and $H(\xi+\tau)+H(\xi-\tau)$ seemed to be discerned by three segmental lines. This suggests that the dry evergreen forest stand is made up of three strata. Hence, the number of strata determined by DAM and SDM were different. Since the boundaries of each segmental line were not considered to be clear in these diagrams, the boundaries between the strata could not be objectively determined. From this viewpoint, this type of graphical method will not be effective, when each stratum is not clearly separated. This problem would cause bias and variation in analyses of forest stratification, such as the determination of the num-

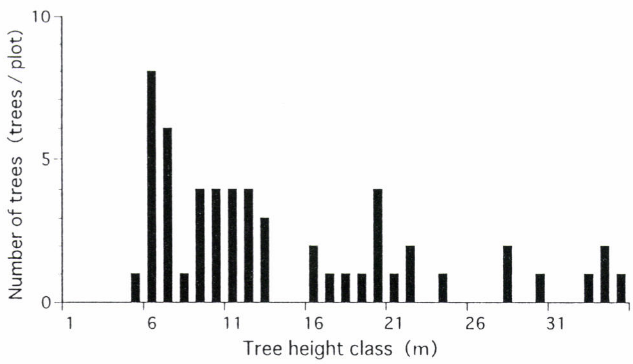

Fig. 6 Tree height histogram for a primary mixed forest stand in Moraballi Creek, British Guiana
Note: Tree height records were read from the profile diagram drawn by DAVIS and RICHARDS (1933).

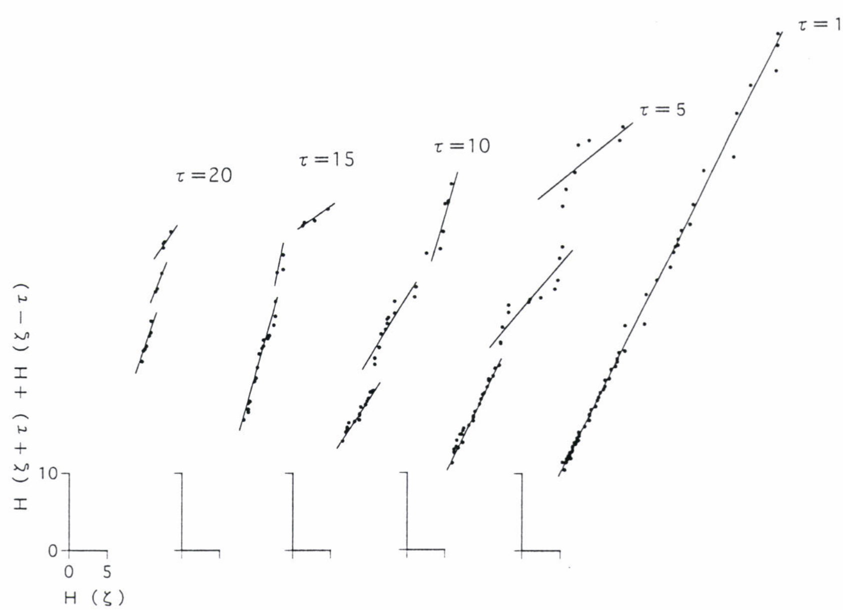

Fig. 7 Some examples of symmetric type difference diagrams for a primary mixed forest stand in Moraballi Creek, British Guiana

Table 3 Thresholds, variance ratios and Q_M values for a primary mixed forest stand determined by DAM

number of strata (M)	thresholds (k_j)	variance ratio (η_M)	Q_M value
2	17	0.752	0.005
3	14,26	0.913	0.118
4	10,16,26	0.955	0.151

ber of strata or the number of trees in each stratum. The crown depth diagram (Ogawa *et al*., 1965), $M-w$ diagram (Hozumi, 1975) and $H-h$ diagram (Okano and Aragami, 1999) will also have the same problem.

Fig. 6 shows the tree height histogram, and Table 3 shows the thresholds, variance ratios and Q_M values determined by DAM for the primary mixed forest stand. Since the Q_M value was maximized when M was four, this stand is considered to be composed of four strata with the thresholds at the 10m, 16m and 26m height classes.

Fig. 7 shows some examples of symmetric type difference diagrams for the primary mixed forest stand. When τ was five or more, the relationships between $H(\xi)$ and $H(\xi+\tau)+H(\xi-\tau)$ also seemed to be discerned by three segmental lines. This suggests that the primary mixed forest stand is made up of three strata. Hence the numbers of strata determined by DAM and SDM were different. Yamakura (1987) said that the number of trees in each stratum could be graphically read with SDM by counting the number of dots aligned on each segment. However, such a procedure would become time- and labor-consuming with an increase in the total number of trees. On the other hand, the number of trees in each stratum can be simply obtained with DAM by the calculation of the product of the probability of occurrence of each stratum ω_j, that gives maximum η, and the total number of trees N. Furthermore,

Table 4 Thresholds, variance ratios and Q_M values for a Japanese cedar even-aged pure forest stand determined by DAM

number of strata (M)	thresholds (k_j)	variance ratio (η_M)	Q_M value
2	9.0	0.689	−0.132
3	8.0,9.5	0.892	0.014
4	7.5,8.5,9.5	0.939	0.011

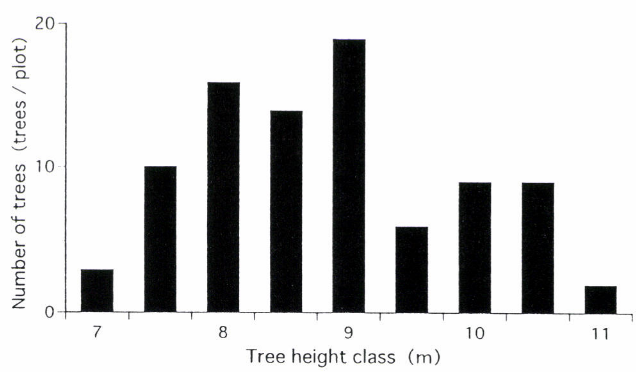

Fig. 8 Tree height histogram for a Japanese cedar even-aged pure forest stand, Japan

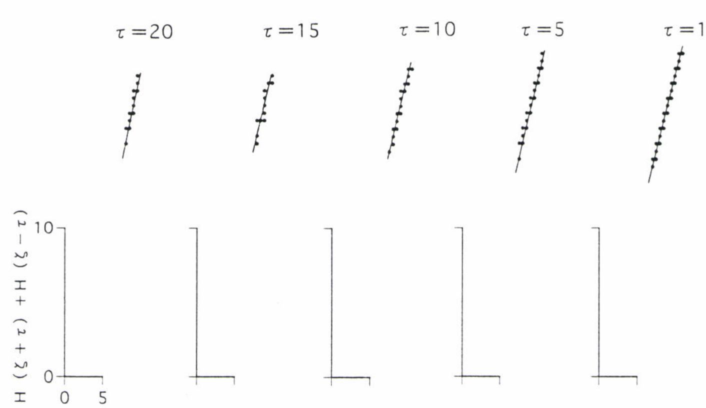

Fig. 9 Some examples of symmetric type difference diagrams for a Japanese cedar even-aged pure forest stand, Japan

the mean tree height class of each stratum can also be simply obtained by eq. 5. These advantages also make DAM one of the most effective methods for analyzing forest stratification.

Fig. 8 shows the tree height histogram, and Table 4 shows the thresholds, variance ratios and Q_M values determined by DAM for the Japanese cedar even-aged pure forest stand. Since the Q_M value was maximized when M was three, this stand is considered to be composed of three strata with the thresholds at the 8.0m and 9.5m height classes.

Fig. 9 shows some examples of symmetric type difference diagrams for the Japanese cedar even-aged pure forest stand. The relationships between $H(\xi)$ and $H(\xi+\tau)+H(\xi-\tau)$ are clearly discerned by a single line. This suggests the even-aged pure forest stand is made up of one stratum. Again the numbers of strata determined by DAM and SDM were different. Since it cannot be judged with DAM whether a forest stand is composed of one stratum or two strata, the numbers of strata of this stand determined by DAM and SDM will be different. It can be said that this point is a disadvantage of DAM and an advantage of SDM.

CONCLUSION

In this paper, DAM was qualitatively compared with SDM by applying both these methods to four types of actual forest stands. The number of strata determined by DAM and SDM were different. Using SDM, cases of forest stands that could not be successfully stratified into several strata were observed, and the number of strata and the boundaries between the strata could not be objectively determined. On the other hand, with DAM, forest stands could be stratified into some strata not subjectively but objectively. However, it could not be judged with DAM whether a forest stand is composed of one stratum or two strata, whereas this was possible with SDM. From these results, it cannot be concluded which method is superior to the other since they have different advantages and disadvantages. It is therefore considered important to choose the appropriate method or to combine the two methods depending on the purpose of analysis. As an example, the following procedure is recommended: First, using graphical methods such as SDM, $M-w$ diagram or $H-h$ diagram, it is judged whether the forest stand is composed of one stratum or more than two strata. Then, if it is judged using graphical methods that the forest stand is composed of more than two strata, the optimal number of strata and the degree of stratification is analyzed using DAM. In contrast, if it is judged using graphical methods that the forest stand is composed of one stratum, the DAM is not used.

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