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JOURNAL OF FOREST PLANNING is a peer-reviewed periodical that publishes articles, reviews, and short communications. It covers all aspects of forest management, modeling, and assessment such as forest inventory, growth and yield modeling, remote sensing and geospatial information technologies for forest management, forest management planning, forest zoning, evaluation of ecosystem services, managerial economics, and silvicultural systems. Manuscripts regarding forest policy, forest economics, forest environmental education, landscape management, climate change mitigation and adaptation strategies, and drone applications for forest management are welcome. The Journal aims to provide a forum for international communication among forest researchers and forestry practitioners who are interested in the above-mentioned fields.

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Spatial and Temporal Patterns of Illegal Logging in Selectively Logged Production Forest: A Case Study in Yedashe, Myanmar

Zar Chi Win[1,2], Nobuya Mizoue[3,*], Tetsuji Ota[4], Guangyu Wang[5], John L. Innes[5], Tsuyoshi Kajisa[6] and Shigejiro Yoshida[3]

ABSTRACT

Illegal logging is a globally important issue, but there is dearth of quantitative information on the spatial and temporal patterns of illegal logging on the ground. We measured the size, species, and ages of stumps from illegally or legally logged trees along a total of 10 km of 20-m-wide transects in traditional production forests of Myanmar. The number and basal area of stumps resulting from illegal logging were 9.93- and 3.89-fold greater, respectively, than those of legal logging. Illegal logging always targeted high-quality trees for timber, but it increased significantly after legal logging. Spatial patterns of illegal logging varied before, during and after legal logging. More illegal logging occurred in areas that were closer to old footpaths before legal logging, but more illegal logging occurred closer to main and logging roads after legal operations. We conclude that current legal logging operations facilitate illegal logging because the construction of logging roads makes it easier for illegal loggers to transport their harvests. Therefore, the government should enforce existing rules that require that logging roads be decommissioned and rendered impassable after the cessation of legal logging operations.

Keywords: illegal logging, legal logging, stump, tree size, tropical forest

INTRODUCTION

Tropical forests are home to more than one-half of Earth's biodiversity, and they have a great influence on climate, but they are suffering from accelerated human disturbances, such as conversion to other land-use types and degradation through hunting, selective logging, and fire (Ahrends et al., 2010; Barlow et al., 2016; Lewis et al., 2015). Such disturbances occur both legally and illegally, making the sustainable management of tropical forests complex and difficult (Lewis et al., 2015; Reboredo, 2013; Vasco et al., 2017). Illegal logging and the associated trade of illegally logged timber have long been serious global issues (Abugre and Kazaare, 2011; Alemagi and Kozak, 2010; Gunes and Elvan, 2005; Hansen and Treue, 2008) with social, economic, and environmental impacts (Gutierrez-Velez and MacDicken, 2008; Reboredo, 2013; Zhang et al., 2016). It has been reported that the amount of illegally logged timber exceeds the amount of legally harvested timber in developing countries (Gan et al., 2016; Kuemmerle et al., 2009), and approximately 15%–30% of the volume of timber traded globally is obtained illegally (Nellemann and INTERPOL Environmental Crime Programme (eds), 2012).

Quantifying the amount of illegal logging is one of the most fundamental steps needed to tackle these issues. By their very nature, statistics on illegal logging are difficult to find, so indirect methods are usually used to estimate illegal logging. Commonly-used methods include trade data discrepancies, wood balance analyses, and import source analyses (Gan et al., 2016). Such methods can provide illegal logging rates at national or regional scales at relatively low cost because they mostly use existing data, such as export/import and domestic timber production data. While overall illegal harvesting rates may be useful for initially characterizing illegal logging,

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further details, e.g., species, geographical origin, and felling agents, are required to devise adequate policy measures to combat illegal logging (Hansen and Treue, 2008). One promising approach for further quantification is to use a time-series derived from remote sensing data, such as that obtained from satellite sensors (Asner et al., 2006; Kuemmerle et al., 2009) and air-borne lasers, but this approach still faces challenges regarding the identification of individual trees and species, especially in natural tropical forests (White et al., 2016). Another possible approach uses field measurements of stumps from illegally- logged trees, which provide detailed information on the size, species, and spatial patterns of such trees (Furukawa et al., 2011; Lund et al., 2015; Scabin et al., 2012). However, no studies have simultaneously compared the stumps resulting from the harvests of illegally and legally obtained trees.

We conducted a field survey along a total of 10 km of 20-m-wide transects to measure the size, species, and ages of stumps from legally and illegally logged trees in natural production forests in Myanmar (Fig. 1), where selective logging forestry, the so-called Myanmar Selection System (MSS), has been conducted since the late 19th century. Under the MSS, tree marking with official hammers before and after logging is normal practice, and enabled us to distinguish legal and illegal stumps in the field. We aimed to reveal the spatial and temporal patterns of illegal logging at the study site, and to highlight how legal logging operations influence illegal logging.

MATERIALS AND METHODS

Study Area

Myanmar has historically famous, beautiful, teak-bearing forests, but these forests are currently experiencing high deforestation and forest degradation rates (Khai et al., 2016; Mon et al., 2012). Forests are important economic assets for nations and local communities, and forests have long been primary national revenue generators. Timber extraction for commercial use is allowed in production forests by a government agency and/or officially licensed timber companies. The extraction of forest products for commercial use without official permission is strictly prohibited. Basic forest products for self-consumption can be extracted from areas specifically designated to meet local needs. Timber production is gradually declining in quantity and quality (Springate-Baginski et al., 2014), while forest areas are rapidly decreasing. Illegal logging is one of the major causes of forest degradation and deforestation in Myanmar (Khai et al., 2016; Thein et al., 2007), and it has long been a chronic socio-environmental issue. As in other countries, it might be possible to classify the types of illegal logging under current legislation in Myanmar as large-scale commercial illegal logging that is conducted through corrupt governance, illegal logging conducted in areas of conflict where the governance is ambiguous, and small-scale community practices, such as the exploitation of timber and wood for firewood and charcoal without permission (Abugre and Kazaare, 2011;

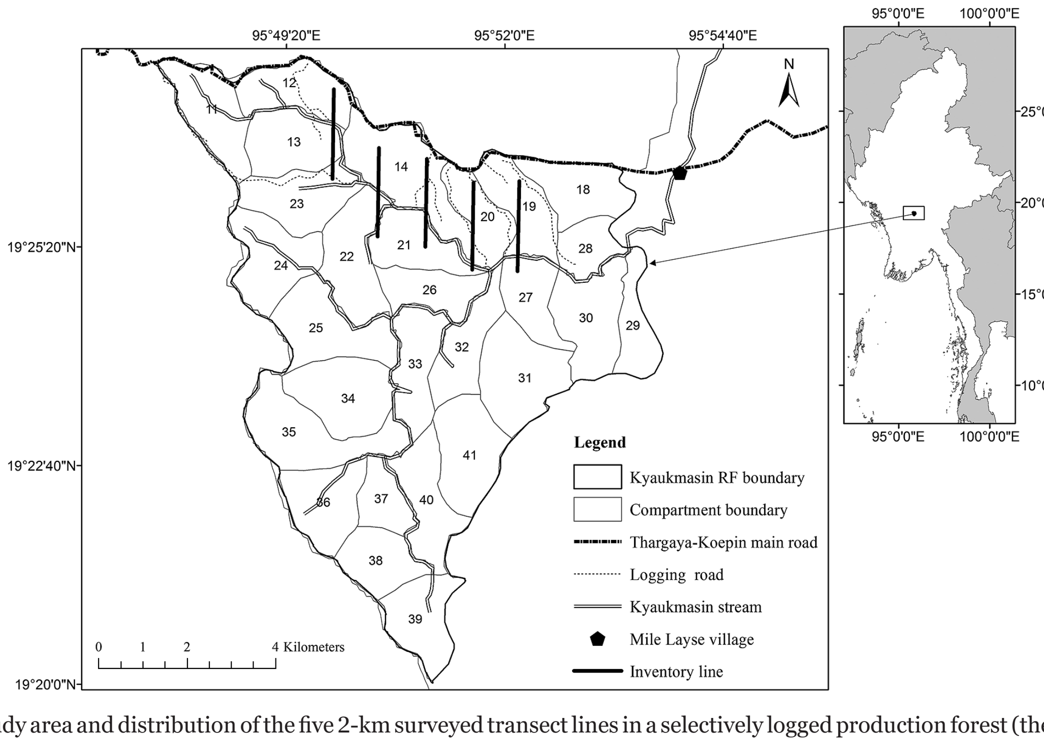

Fig. 1 Study area and distribution of the five 2-km surveyed transect lines in a selectively logged production forest (the Kyaukmasin Reserve Forest) in Yedashe Township, Bago Region, Myanmar. The World Borders Dataset provided by Thematic Mapping (http://thematicmapping.org/) was used as the country border. An administrative boundary provided by the Myanmar Information Management Unit (http://www.themimu.info/) was used as the township boundary. Data of land cover, the Reserve Forest boundary, and the compartment boundaries including compartment numbers were obtained from the Forest Department of Myanmar.

Table 1 Legal timber extraction in the nine surveyed compartments of the Kyaukmasin Reserve Forest

Compartment	Area (ha)	Logging during study period		
		Logging year	Number of trees harvested (tree ha^{-1})	Basal area harvested (m^2 ha^{-1})
12	253.8	2008	1.40	0.75
		2010	2.02	0.95
13	302.0	2010	2.42	1.17
14	333.5	2008	4.17	2.24
19	236.8	2009	2.27	1.06
20	210.8	2009	1.92	0.86
21	213.7	2008	1.19	0.63
22	304.5	2008	4.10	2.07
		2011	2.20	1.00
23	274.5	2008	2.37	1.31
27	161.5	2009	1.94	0.81
Average over compartments (mean ± SE)			2.89 ± 0.52	1.43 ± 0.26

Springate-Baginski et al., 2014). Our study focused on logging that was not officially sanctioned.

Our study site, the Kyaukmasin Reserve Forest is a timber production forest, where non-commercial use is prohibited. It is located in the south-central part of Myanmar and has an area of 7,177 ha (Fig. 1) The major forest type is a moist upper mixed deciduous forest, which is the classic habitat for teak and many other valuable timber species. As shown in Fig. 1, our sample lines mainly transected nine compartments, 12, 13, 14, 19, 20, 21, 22, 23, and 27 in the Kyaukmasin Reserve Forest. The main permanent road, the Thargaya-Koepin road, parallels the boundary of our surveyed Reserve Forest, and the Kyaukmasin stream flows through the middle of the Reserve Forest, although its flow is seasonal.

To understand the history of government logging in the study area, secondary data from the Yedashe Township Forest Department and the Taungoo District Forest Department were used (Table 1). Legal timber extraction stopped in the study area in 2015, despite our study area being one of the best production Reserve Forests in the past. During the study period from 2005 to 2015, timber extraction was conducted once or twice in every compartment in which our inventory lines were located. The average intensity of legal logging was 2.89 ± 0.52 tree ha^{-1}, and the basal area removed was 1.43 ± 0.26 m^2 ha^{-1} for teak and other hardwood species during the study period (Table 1). In addition, we checked the logging history from 2000 and 2004 and found that government logging operations were also conducted in 2004 in compartments 12 and 13.

Data Collection

For the field inventory, an equal-distance, belt-transect sampling method was applied, and the starting point of the line was selected subjectively. The width of the transect was 20 m for stumps, and standing trees within 5 m of the center line of the transect were also recorded. The starting point was set approximately 50 m away from the main road, the Thargaya-Koepin road, and the length of the lines was 2 km from north to south with a between-line interval of 1 km. There were five inventory lines in our survey (Fig. 1). The field survey was conducted initially in January 2015 for one line and then in December 2015 for the other four lines.

Within 5 m of the center line, all standing trees with a DBH ≥10 cm were recorded in all the transects, except in the first line where only trees with a DBH ≥20 cm were recorded. The measured parameters were DBH, species, elevation, and location. Within 10 m of the center line, all existing stumps ≥10 cm diameter at stump height (DSH) were recorded, and the parameters were DSH, species, elevation, location, estimated stump age, and stump types, such as legally or illegally cut. Elevation and location of trees and stumps were measured using the TruPulse 360 Laser Rangefinder.

To estimate stump age, our research team participated in training exercises by visiting official government logging sites and permanent sample plots, and then checking the conditions of old stumps and their respective ages. We also learned from experienced local people. Estimation of stump age and species classification were performed with the assistance of local forest department staff and experienced villagers. Stump age was identified from 0 to 10 years old and >10 years, based on the remaining sprouts, bark, and wood color. Stump types were classified by size, height, and the hammer sign on the stumps that were done by the Myanmar Timber Enterprise.

In Myanmar, the government has paid much attention to ensure the legality of logging operations through the use of tree hammer-marking and inspections by two organizations, the Forest Department (FD) and the Myanmar Timber Enterprise (MTE). First, the FD must select exploitable trees that have attained the prescribed minimum exploitable limits. These are all >50 cm, with minimum diameters (DBH) being 58 cm, 63 cm, and 68 cm, etc., depending on species. Marking is usually performed on blazes made on the lowest part and above the 1.3 m measuring point for DBH of the trunk of trees selected for felling. Then, the marked trees are felled by the MTE. In general, the rule is to cut the selected tree, leaving the lower blaze on the stump, and keeping the height of the stumps as low as possible. After cutting, the MTE marks the surface of the remaining stump and cut logs using a hammer, and the FD has to check the marking and cut height of stumps. Hammer-marked information on the stump surface includes tree number, log number from the single tree, and the code of a person in charge. The MTE uses elephants to skid logs to log-landings built temporarily in forests. At the log-landing, the MTE marks the cut surface of the logs using a hammer and the FD has to inspect the MTE's markings. The MTE is responsible for transporting logs from the log-landings to log-yards. During transportation, the FD has to inspect the hammer markings on the logs and the associated documentation.

During our field survey, we tried to find the official hammer sign when the stumps' size was larger than the fixed minimum exploitable limit. Stumps without an official hummer mark on the surface were classified as illegal, and all stumps that were smaller than the prescribed minimum exploitable limit were also classified as illegal. In our survey, three types of stumps were found: legal stumps, illegal stumps, and unknown stumps, which could not be confirmed because they were too old, decayed, and/or destroyed. Grading of the quality for timber and charcoal was conducted by a group discussion with local charcoal makers and illegal loggers. For physical features, such as distances from roads and permanent human settlements, road networks were tracked by the Global Positioning System, and the nearest permanent village location was recorded by the Global Positioning System. Stream path was digitized from the 1:50000 Universal Transverse Mercator Projection (UTM, 2003 edition, Sheet No. 1995 15) map from the Forest Department, Myanmar using ArcMap 10.1. Distance from streams was calculated in ArcGIS 10.1 using the spatial tool. Slope was calculated in ArcGIS using a 30-m resolution digital elevation model that has been generated from the Shuttle Radar Topography Mission (SRTM) and obtained from the archives of the U.S. Geological Survey (2017).

Accuracy of Stump Measurements

The accuracy of our stump measurements was evaluated by comparison with official government records of the logging of each compartment (Table 1). We found a total of 395 stumps within the 20 ha of transects, of which 296 (75%) and 99 (25%) stumps were ≤10 years old and >10 years old, respectively (Table 2). Among the 296 stumps that were ≤10 years old, only one stump was unknown, because the condition of the cut surface and bark was such that we could not identify the presence of the government hammer mark, while the other 295 stumps were identified as illegal (268 stumps) or legal (27 stumps). In contrast, among the 99 stumps that were >10 years old, only 10 stumps (10%) were identified as illegal (five stumps) or legal (five stumps), while most (89 stumps, 90%) were unknown because of poor stump conditions. Decay and/or breakage mostly prevented us from identifying the presence of official hammer marks. Because we understood that the measurements of stump types and ages were difficult if the stumps were >10 years old, our data analysis used only the 295 stumps that were ≤10 years old, excluding one unknown tree.

According to governmental records, the intensity of

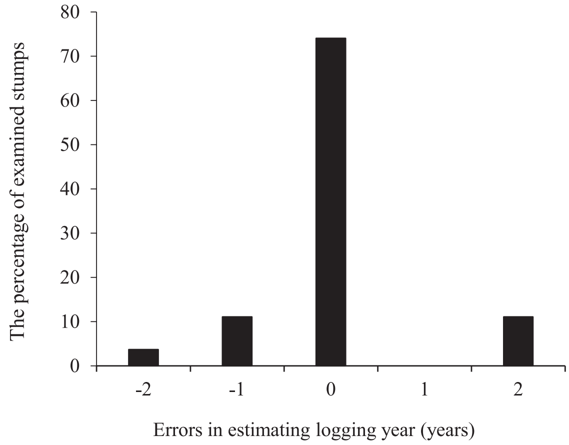

Fig. 2 Errors in stump age estimates of our field measurements compared with official governmental records.

legal logging for the 10-year period of the field survey was 2.89 ± 0.52 trees ha^{-1} (mean ± standard error (SE)), and it ranged from 1.19 to 6.30 trees ha^{-1} among the nine compartments (Table 1). However, our field measurements showed that the intensity of legal logging for stumps that were ≤10 years old was 1.35 ± 0.40 trees ha^{-1} (Table 2), which is significantly lower than the official record by 1.54 trees ha^{-1} ($p < 0.01$). Therefore, our estimation of the amount of legal stumps may be conservative compared with the average logging intensity of the nine compartments. Such an underestimation is likely to come from our sampling design, in which the five 2-km transects did not evenly cover the entire areas of the nine compartments and some of our transects covered very small proportions of the compartment areas (Fig. 1).

Our estimation of stump ages for legal stumps ranged from 5 to 8 years old for 27 stumps and >10 years for five stumps. The exact agreement in stump age between our field estimates and government records of the logging year was 74% for a total of 27 stumps (Fig. 2). Differences of 1 and 2 years were found for three (11%) and four stumps (15%), respectively, and no sample had an error that was greater than 2 years. In view of these measurement errors of stump ages, even though they were small, we categorized stump ages into "before", "during", and "after" legal logging operations for statistical modeling, rather than using annual data, when we analyzed the effects of years before and after legal logging operations (Fig. 4). The category "during" includes 2 years (0 and +1 years): the year of tree-marking, felling, and skidding and then the following year of skidding and transportation. The "before" and "after" categories ranged from −1 to −3 years and from +2 to +5 years, respectively, because some compartments did not have stump-age estimations beyond these timeframes (Fig. 4). In addition, we did not use the data from compartments 12, 13 and 22 when examining the effects of the number of years relative to the legal logging operations, because there were two to three legal logging operations during a very short interval (an interval of three years between 2008 and 2011 in compartment 22 and an interval of six years from 2004 to 2010 in compartments 12 and 13)

(Table 1) and we could not differentiate the effects of these logging operations.

Data Analysis

Basal area at breast height of the stumps was calculated using the stem shape model (Thein et al., 2007) as follows.

$$\mathrm{DBH} = \mathrm{DSH}/1.028\, h^{-0.114} \quad (1)$$

where DSH is the diameter of the stump, and h is the height of the stump from the ground to the point where the diameter was measured.

The data analysis was undertaken in two steps. First, we presented descriptive statistics for the number, basal area at breast height, species composition, and structures of the size and age of the illegal stumps. Second, to identify the biophysical factors affecting the probability of illegal logging, a generalized linear model (GLM) with a binomial distribution and a logit link function was applied in R ver. 3.2.4 (R Core Team, 2016). We explored four GLMs. In Model 1, the timing of illegal logging with respect to legal logging (before, during, or after legal logging operations) was used as a categorical independent variable; Models 2, 3 and 4 were the GLMs that focused on illegal logging before, during and after legal logging, respectively. For all four models, the dependent variable was whether the tree was standing (0) or had been cut illegally (1), and the independent variables were DBH (cm), quality for timber (grades 1 to 4), quality for charcoal (grades 1 to 4), elevation (km), slope (degree), distance from the main permanent road (km), distance from logging roads (km) that were constructed for temporary transportation operations, distance from footpaths (km), distance from the stream (km), and distance from permanent human residences (nearest village) (km) (Table 3). Before applying the GLMs, we checked multi-collinearity among independent variables and confirmed that there was no collinearity with a Variance Inflation Factor of less than 5 (Fox et al., 2018). Selection of the best model for each GLM was made according to the Akaike information criterion (AIC).

Table 2 The numbers of stumps and standing trees per hectare in the study area

	Total stumps for 20 ha	Tree/stump number (stem ha^{-1}) (mean ± SE)	Basal area (m^2 ha^{-1}) (mean ± SE)
Stumps within 10 years			
(a) Illegal stumps	268	13.40 ± 1.68	2.96 ± 0.57
(b) Government stumps	27	1.35 ± 0.40	0.76 ± 0.27
(c) Unknown	1	0.05 ± 0.05	0.04 ± 0.04
Stumps over 10 years			
(a) Illegal stumps	5	0.25 ± 0.16	0.05 ± 0.05
(b) Government stumps	5	0.25 ± 0.14	0.11 ± 0.08
(c) Unknown	89	4.45 ± 1.19	1.80 ± 0.35
Standing trees		154.23 ± 8.76	16.78 ± 0.88

Table 3 Characteristics of the dependent and independent variables

Variables	Unit	Min.	Max.	Mean
Dependent Variable				
Tendency of illegal cutting	Binary (0, 1)			
Standing Tree (0)				
Being cut (illegal stumps) (1)				
Independent Variables				
DBH	cm	10	200	35.23
Quality for charcoal	Ordered categorical	1	4	2.93
Grade 1, 2, 3, 4				
Quality for timber	Ordered categorical	1	4	3.18
Grade 1, 2, 3, 4				
Elevation	km	0.25	0.37	0.32
Slope	degree	0.68	26.39	10.90
Distance from main road	km	0.20	2.45	1.27
Distance from old footpath	km	0	0.80	0.22
Distance from logging road	km	0	1.08	0.28
Distance from stream	km	0	1.92	0.70
Distance from permanent village	km	3.44	7.43	5.10
Timing of illegal logging relative to legal logging	Categorical			
(a) During government logging				
(b) After government logging				
(c) Before government logging				

Note: The dependent variable is in binary form, and diameter at breast height (DBH), elevation, slope, and distances from permanent villages, the main road, and the stream are continuous; illegal harvesting years relative to legal logging are categorical; and the remaining are ordered categorical variables.

RESULTS AND DISCUSSION

General Characteristics of Illegal Logging

The total of 20 ha of transects included 395 stumps, of which 32 were legal and 273 were illegal, while the legality of the remaining 90 stumps was unknown. During the 10-year study period, the illegal logging intensity was 13.40 ± 1.68 stumps ha^{-1}, and the basal area removed was 2.96 ± 0.57 m^2 ha^{-1}, 9.93- and 3.89-fold higher, respectively, than those of government-approved legal logging (Table 2). Illegal stumps were found in every diameter class, but the highest percentages (approximately 25%) of illegal stumps (relative to the total number of standing trees and stumps) were found in the largest diameter size classes (Fig. 3). In contrast, legal stumps were found only in size classes with a diameter at breast height (DBH; measured 1.3 m above the ground) ≥50 cm, which is larger than the pre-determined minimum diameter limit (MDL). The MDL is generally determined based on potential size and growth rates of adult trees and it ranged from 53 to 78 cm depending on the species. Forty species from 33 genera and 19 families were found among the illegal stumps (Table 4), with the two most abundant species (teak (*Tectona grandis* L.f.) and pyinkado (*Xylia xylocarpa* Roxb. Taub.)) accounting for 64.92% of the illegal stumps. These species are the most valuable and the best quality species for timber, and the latter is also the best for charcoal making.

Table 4 Species characteristics and composition of illegal stumps over 10 years

Local Name	Scientific Name	Quality for timber	Quality for charcoal	Total number of stumps	Relative density
Teak	*Tectona grandis*	1	4	106	39.55%
Pyinkado	*Xylia xylocarpa*	1	1	68	25.37%
Kyetyo	*Vitex pubescens*	4	2	12	4.47%
Binga	*Mitragyna rotundifolia*	4	2	9	3.36%
Seikchi	*Bridelia retusa*	4	4	8	2.99%
Taukkyan	*Terminalia tomentosa*	4	3	8	2.99%
Dwani	*Eriolaena candollei*	4	4	4	1.49%
Gyo	*Schleichera oleosa*	4	1	4	1.49%
Ingyin	*Shorea siamensis*	2	1	4	1.49%
Petthan	*Haplophragma adenophyllum*	4	3	3	1.12%
Thadi	*Protium serrata*	3	4	3	1.12%
Thit-pagan	*Millettia brandisiana*	4	4	3	1.12%
Yon	*Anogeissus acuminata*	4	1	3	1.12%
Chinyok	*Garuga pinnata*	3	4	2	0.75%
Leza	*Lagerstroemia tomentosa*	4	3	2	0.75%
Madama	*Dalbergia ovata*	4	2	2	0.75%
Thabut-gyi	*Miliusa velutina*	4	4	2	0.75%
Thetyin-gyi	*Croton oblongifolius*	4	4	2	0.75%
Zaungbale	*Lagerstroemia villosa*	4	3	2	0.75%
Didu	*Bombax insigne*	3	4	1	0.37%
In	*Dipterocarpus tuberculatus*	2	4	1	0.37%
Kwe-tayaw	*Grewia humilis*	4	3	1	0.37%
Kyaung-sha	*Oroxylum indicum*	4	4	1	0.37%
Ma-u-lettan-she	*Anthocephalus cadamba*	4	4	1	0.37%
Mahlwa	*Makhamia stipulata*	4	4	1	0.37%
Ngu	*Cassia fistula*	4	2	1	0.37%
Ondon	*Litsea laurifolia*	4	4	1	0.37%
Other	*NA*	4	4	1	0.37%
Padauk	*Pterocarpus macrocarpus*	1	4	1	0.37%
Pet-wun	*Berrya mollis*	4	4	1	0.37%
Shaw	*Sterculia urens*	4	4	1	0.37%
Shaw-wa	*Sterculia ornata*	4	4	1	0.37%
Tabu	*Harrisonia perforata*	4	4	1	0.37%
Thanat	*Cordia mixa*	4	4	1	0.37%
Thit-magyi	*Albizia odoratissima*	4	2	1	0.37%
Thit-pok	*Dalbergia kurzii*	4	4	1	0.37%
Thit-seint	*Terminalia bellerica*	4	2	1	0.37%
Thit-ya	*Shorea obtusa*	2	1	1	0.37%
Yetetbar	*NA*	4	3	1	0.37%
Yin-daik	*Dalbergia cultrata*	4	2	1	0.37%
	Total			268	100.00%

Note: Regarding quality for timber, a grade of 1 means the best quality and most economically valuable species; a grade of 2 represents good timber whose market price is relatively low; a grade of 3 indicates lesser used and less valuable species; and a grade of 4 indicates timber for which there is no use or market demand. Regarding quality for charcoal, a grade of 1 means the best and most preferred species for charcoal making; a grade of 2 indicates a good species; a grade of 3 indicates species that are of poor quality for charcoal making, but which are used when there is no other choice; and a grade of 4 indicates species that are not used to make charcoal.

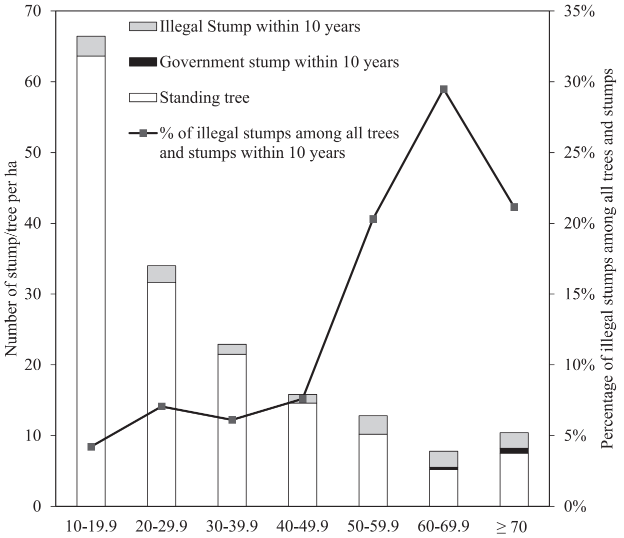

Fig. 3 Diameter distribution of illegal and legal stumps, unknown stumps and standing trees, and the percentage of illegal logging among all observed trees and stumps in 10-m-wide transects.

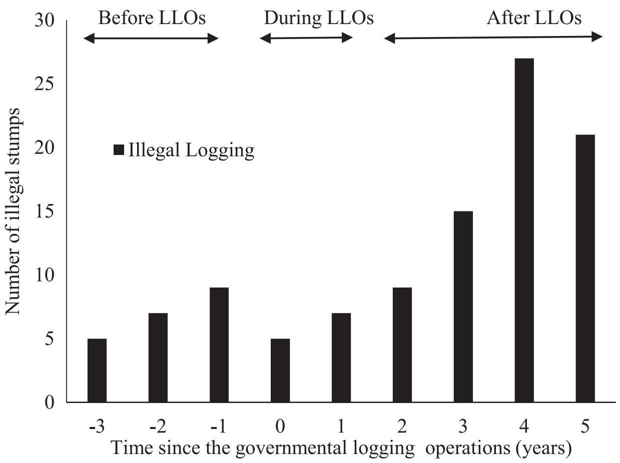

Fig. 4 Timing of illegal logging in the years before, during, and after legal logging operations (LLOs). Year 0 is for tree-marking, felling, and skidding, and year 1 is for skidding and transportation. We categorized the years relative to the legal operations into "before" (from −1 to −3 years), "during" (0 and +1 years), and "after" (from +2 to +5 years).

Illegally logged stumps were identified from before, during, and after legal logging, but there was a significant increase in the number of illegal stumps occurring after the legal logging operations (Fig. 4). In addition, the number of illegal stumps tended to be larger in areas that were closer to main roads, logging roads and old footpaths (Fig. 5).

The logging intensity under the MSS is regulated using an annual allowable cut (AAC) formula. The principle of the AAC is to ensure a sustainable stock of commercial trees that is larger than the MDL, as well as a sustainable yield, using a 30-year cutting cycle. The key parameters of the AAC calculation are the numbers and mortality rates of current commercial trees that are larger than the MDL, as well the number and mortality rates of future commercial trees, which are assumed to be 10 cm less than the MDL, calculated over a 30-year period. In our study, illegal logging rates (approximately 25%) for current and future commercial trees were much higher than the 5% or 10% natural mortality assumed for current and future commercial trees, respectively, which are the rates adopted in the AAC calculation of Myanmar. In short, our field evidence clearly revealed a much higher intensity of illegal logging, especially of large trees, compared with the government's assumed figures for a sustained yield. The observed rate of illegal logging will result in a large reduction of the future yield and biodiversity of production forests in the area, especially for timber species (van Gardingen et al., 2006; Putz et al., 2008). Therefore, restoration of such degraded production forests is the important matter to the Government (Lamb et al., 2005).

Temporal and Spatial Patterns of Illegal Logging

The first GLM (Model 1) confirmed that the probability of illegal harvesting increased significantly after legal logging operations. The quality of timber was the only independent variable that consistently had the same influence for the cases of before (Model 2), during (Model 3) and after (Model 4) legal operations (Table 5), indicating that illegal logging targeted higher-quality trees. In contrast, other variables had different effects on the probability of illegal logging in the three models (Table 5). As an example of the GLMs' predictions, Fig. 6 shows how timber quality and distance from footpaths or logging roads influence the probability of illegal logging before, during and after legal logging. Before the legal logging operation, illegal logging increased in areas that were closer to footpaths (Fig. 6a). On the other hand, during the legal operation, areas that were closer to old footpaths (Fig. 6b), main road and stream had less probability of illegal logging. Distance from logging roads was significant only after the legal operation (Fig. 6c). Larger trees were more subjected to illegal logging before and during the legal logging, but this was not the case after the legal operations.

Most selective logging operations in the tropics facilitate access to forests by expanding forest road networks (Laurance et al., 2009), and roads play a key role in opening up forests to illegal activities (Kirby et al., 2006; Laurance et al., 2009) and deforestation (Asner et al., 2006; Freitas et al., 2010). In the Brazilian Amazon, logged forests are 400% more likely to be deforested than un-logged forests (Asner et al., 2006). Our findings showed that illegal logging increased significantly after legal logging operations, compared with before or during the legal operations. During legal logging operations, temporary logging roads are built using bulldozers so that trucks can transport logs from log-landings to main roads, and such roads are expected to degrade in the following years through soil erosion and gullying, processes that are common on exposed soils in the humid and steep conditions of many production forests in Myanmar. In addition, Myanmar forestry rules stipulate that logging roads are to be closed (e.g., by destroying key bridges or otherwise rendering the road

Table 5 The estimates of the GLMs explaining the probability of an illegal stump
Four different GLMs were estimated; Models for illegal logging (1) using the timing relative to government logging as independent variable, (2) before government logging, (3) during government logging and (4) after government logging. The best-model selection for each GLM was based on AIC.

Independent variables	Estimate			
	Model 1 for all the timing of illegal logging	Model 2 before government logging	Model 3 during government logging	Model 4 after government logging
(Intercept)	−9.6422 ***	−3.2093 ***	−31.5372 ***	−9.1090 ***
DBH	0.0138 ***	0.0271 ***	0.0296 *	
Quality for timber	−0.5913 ***	−1.2166 ***	−0.8797 **	−0.4906 ***
Quality for charcoal				
Elevation	16.1658 **		52.7622 *	21.7692 **
Slope	−0.0370			
Distance from main road			3.2773 **	−0.6659 *
Distance from old footpath	1.7417 ***	−3.0457 *	4.7042 ***	2.6666 ***
Distance from logging road	−1.5709 **			−2.9101 ***
Distance from stream	0.5028 *		4.0334 **	
Distance from permanent village				
Timing of illegal logging relative to legal logging		NA	NA	NA
(a) During government logging	(reference)			
(b) After government logging	1.2989 ***			
(c) Before government logging	0.0913			

Note: An * indicates statistical significance: ***, 0.001; **, 0.01; and *, 0.05. NA indicates that this variable was not used for GLM.

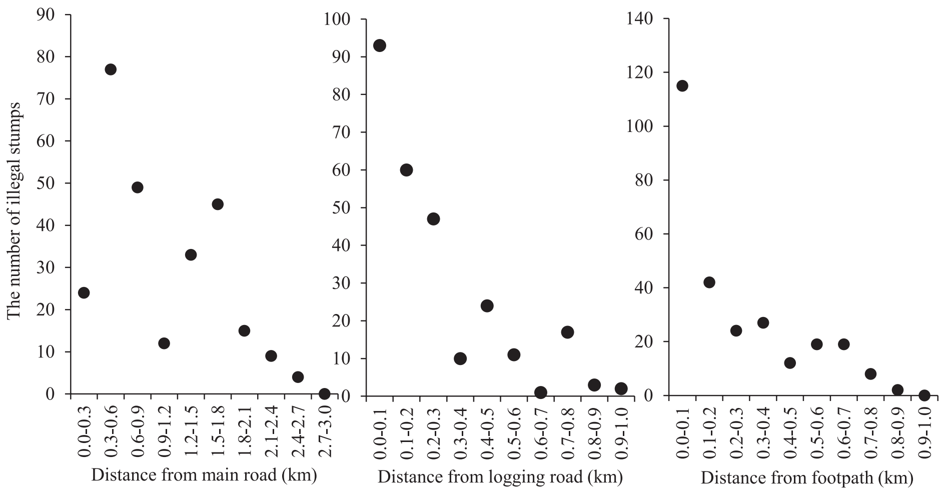

Fig. 5 The number of illegal stumps in relation with distance from main road, logging road and old footpath.

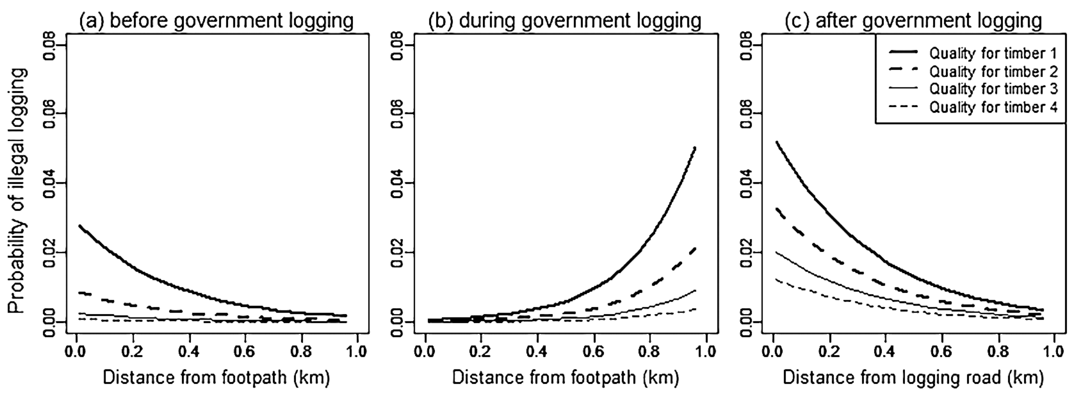

Fig. 6 Changes in the probability of illegal logging over different timber qualities and distance from footpath or logging road before, during, and after legal logging.

impassable) (Laurance et al., 2009) after harvest operations to avoid illegal transportation activities. However, our field observations confirmed that the conditions of most logging roads were good enough for transporting logs using trucks, even several years after the cessation of legal logging operations. This may be the reason why illegal logging was more likely closer to logging roads. It is unknown why the road conditions were maintained years after the cessation of legal logging, but the repeated use yearly by illegal loggers might help maintain the conditions. Nevertheless, our results indicate that logging roads that were originally constructed for legal logging operations facilitate more illegal logging.

Distance from logging roads was significant only after legal operations (Table 5, Fig. 6c). In contrast, distance from old footpaths was significant before legal operations with more illegal logging occurring at smaller distances from old footpaths (Table 5, Fig. 6a). This indicates that illegal loggers tended to use old footpaths for transportation in areas where there are no logging roads. Conversely, during legal logging operations, illegal logging increased in areas that were far from old footpaths (Fig. 6b), main road and stream. At the start of legal operations, FD staff enters logging sites via main roads and footpaths to mark trees to be harvested, and then MTE staff fell and skid trees on the spot. During these operations, it is common for official staff members to stay overnight in temporary camps, which are located near streams. Such extensive activity of governmental staff near main roads, footpaths and streams would be one reason why less illegal logging occurred near these areas during legal operations (Table 5, Fig. 6b).

Elevation is one of the most important biophysical factors affecting deforestation with more deforestation likely to occur at lower elevations (Htun et al., 2013; Lonn et al., 2018). In contrast, differing from our original assumption, illegal logging was more likely in higher elevations during and after legal logging. The elevation range in our study was relatively narrow, ranging from 249.2 m to 382.2 m. According to our observations during the field inventory, most of the lower elevation areas were located in valleys, which seemed to make it difficult for illegal loggers to skid logs as they often use buffaloes or oxen to skid logs to logging roads, which are mainly located on ridges and/or upper slopes. This could explain why there was more illegal logging at higher elevations.

There are mainly two types of illegal logging: one for timber and the other for charcoal (Khai et al., 2016). Under better forest conditions, where commercial and large trees are present before or just after legal logging operations under a long cutting cycle, illegal loggers target large trees for timber production (Khai et al., 2016). However, as large commercial trees become less available in degraded forests, various sizes of trees are harvested for charcoal making. Our GLM results on DBH (Table 5) showed that illegal logging for larger trees increased before and during legal operations, but such size dependency was absent after legal operation. This implies that forest degradation, in terms of reduction in the availability of large trees, became substantial after legal logging.

It was beyond our study objectives to identify who was involved in the illegal logging, but local villagers might be related directly or indirectly to illegal logging even though distance from the village was not selected in the four best models (Table 5). Local people are not allowed to extract forest products from production forests (the forests examined in this study were all gazetted production forests), but they are permitted to use some Reserved Forests for subsistence use. However, it is not clear whether the designated Reserved Forests can meet local demand. As in other tropical counties, the Myanmar government has increased the area of community-based forestry sites from 4,000 ha in 2001 to 41,397 ha in 2009 (Hlaing and Inoue, 2013), and the latest information suggests that the area is now 161,023 ha. Community forestry is expected to achieve win-win outcomes for forest conservation and livelihood improvement. The effective implementation of community forestry could provide a means to reduce illegal logging in production forests.

CONCLUSIONS

Industrial timber production is currently occurring in 28% of tropical forests worldwide (Laurance et al., 2009). In Myanmar, production forests account for 35% of the total forest, and they have been managed by the Myanmar Selection System for three centuries. However, they are suffering from increasing forest degradation, as opposed to deforestation (Mon et al., 2012, 2010). Our 10 km-transect surveys provide evidence that illegal logging is common in Myanmar production forests and the major factor responsible for forest degradation. This finding confirms insights arising from remote sensing (Mon et al., 2012) and field observations in a study with a very limited sample size (only two 1-ha plots) (Khai et al., 2016). High-intensity illegal logging of large trees of important timber species will lead to further forest degradation because logging intensity is the most influential factor affecting biodiversity (Chaudhary et al., 2016; Putz et al., 2008) and sustained yield (van Gardingen et al., 2006). We conclude that illegal logging is facilitated by logging roads that were built for legal logging operations, suggesting that if further roads are to be built, the government should enforce existing rules that require that logging roads be closed shortly after the cessation of legal logging operations.

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