Human disturbance and stand dynamics in selectively logged production forests in Myanmar

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Human Disturbance and Stand Dynamics in Selectively Logged Production Forests in Myanmar

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By

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Abbreviation

AAC	= Annual Allowable Cut
CON	= Conventional Logging
DBH	= Diameter at Breast Height
EITI	= Extractive Industries Transparency Initiative
FAO	= Food and Agriculture Organization of United Nations
FC	= Felling Cycle
FD	= Forest Department
FMU	= Forest Management Unit
GLMM	= Generalize Linear Mixed Model
Ha	= Hectare
HSWC	= Hardwood Supply Working Cycle
ITTO	= International Tropical Timber Organization
LMDF	= Lower Mixed Deciduous Forest
MDCL	= Minimum Diameter Cutting Limit
MTE	= Myanmar Timber Enterprise
MUMD	= Moist Upper Mixed Deciduous Forest
NBSAP	= National Biodiversity Strategy and Action Plan (FD, Myanmar)
PFE	= Permanent Forest Estate
PPF	= Protected Public Forest
PSD,FD	= Planning & Statistics Division, Forest Department
REDD+	= Reducing Emissions from Deforestation and Forest Degradation, Conservation, Sustainable Management of Forests and Enhancement of Forest Carbon Stocks
RF	= Reserved Forest
RIL	= Reduced Impact Logging
TSWC	= Teak Selection Working Cycle

Summary

The conservation values of selectively logged forests, which shares approximately 20% of the world's tropical forests have been considered important from the viewpoints of timber production, global carbon cycle and biodiversity conservation. A critical global concern in recent decades is that selective logging may cause tropical forests degradation and associated carbon emission and then leading to deforestation. When the Myanmar forest policy had to exercise one-decade fallow period in the legendary Bago Yoma production forests after the 160-year history of Myanmar selection system (MSS), the question is what the underlying causes are or to what extent the MSS operations are responsible for the prevailing problem of production forest degradation? This study aims to evaluate the impact of human disturbances and stand dynamics at post-harvest condition in the selectively logged production forests, and to identify possible ways to improve the MSS operations (*Chapter 1)*. For the research, we established 9-ha rectangular plots (300 ×300 m) at four different site; one at Bago Yoma in 2011 and another three plots at Katha during 2017, respectively.

In *Chapter 2*, the overview of selectively logged production forests in Myanmar and the MSS are briefly introduced. In tropical Myanmar, the production forests were found mainly in mixed deciduous forests, encompassing about 38% of the total forests. *Tectona grandis* (teak) and *Xylia xylocarpa*, as the two main characterizing species proportion approximately one third of the forest stocks while other species seldom exceeds 3% or one tree ha-^{1}. The MSS, evolved in 1860s, is oriented toward the sustainable production of teak, from which the basic theories and practices are subsequently applied in other forests. Under it, harvesting tree is determined by prescribed minimum diameter cutting limit (MDCL) and a 30-year felling cycle. Elephant is mainly use in the skidding operation in the logging sites. After 160-year experiences of selectively logging, logging was temporarily banned for one year in 2016, and the legendary Bago Yoma, the main extraction site has given 10-year fallow period. When the logging was resumed in 2017, the timber harvesting plan set at the national scale was to extract only 55% of teak and 33% of non-teak hardwood, respectively than the prescribed annual yield. However, it is still unknown to what extent the MSS operation will be responsible for disturbances at the operational level or how to improve the MSS operation.

Chapter 3 aimed to evaluate the levels of MSS disturbance to standing trees and the ground as compared with those reported for other tropical countries, and to identify possible ways to improve MSS operations. At each of four study sites (nine 1-ha subplots), all the living trees ≥ 10 cm dimeter at breast height (DBH) and their damage caused from felling trees were measured in two of the subplots,

and the harvested trees and the disturbance to the ground were measured in all the nine subplots. Harvesting intensity varied from 0 to 18 trees ha-^{1} (143.7 m^3 ha^{-1}) with the mean of 5.2 trees ha^{-1} (39.0 m^3 ha^{-1}) among a total of 36 1-ha subplots. The harvesting intensity was linearly related to felling damage (% in number) to residual trees and bamboo clumps, and to ground disturbance (% in area) (roads, log landings, skid trails, and machine-disturbed areas). These linear relationships for MSS were at the lowest level of, or not significantly different from, those reported in other studies. The lowest level of ground disturbance is because of the use of elephants for skidding, resulting in no visible ground disturbance only a few months after the operation. However, this low impact was confined only to low harvesting intensity ≤ 5 trees ha^{-1} (~ 25 m^3 ha^{-1}). When felling intensity exceeded 10 trees/ha (98 m^3 ha^{-1}) the ground disturbed area under MSS achieved even higher than those RIL studies. In high felling intensity of MSS case, 36 % of total harvested trees were too large (> 100 cm DBH) for elephant skidding, and so machines were used instead. The use of machines for skidding resulted in a greater proportion of disturbed area (2.5% of the area at Site 4). To minimize disturbance to residual trees and the ground, we suggest to limit the maximum harvesting intensity and avoid harvesting trees too big for elephants to drag. Retaining such large trees may also be beneficial to provide seed sources and for biodiversity conservation.

In *Chapter 4*, a proposed tree-based approach was applied to evaluate the felling damage to residual trees in a tropical mixed deciduous forest in Bago Yoma, Myanmar and compared the cases with semi-evergreen forests of Cambodia. The logging damage was assessed in twenty 0.1-ha plots (25 m × 40 m) each of which contained the stump and crown of one felled tree, and multinomial logistic regression was used to quantify the probability of the felled tree causing severe, slight, or no damage to residual trees. In both cases of Myanmar and Cambodia, severe damage was dependent on the size of the residual and felled trees, while slight damage was independent of the size of felled trees. There was no slight damage of residual trees with ≥50 cm diameter at breast height (DBH) in Myanmar, whereas slight damage increased with residual tree size in Cambodia and in tropical rain forests of other countries. Additionally, the probability of increasingly severe damage with increasing DBH of the felled trees was higher in Myanmar than in Cambodia; one of the reasons may be the steeper terrain at the Myanmar site. In overall, the residual tree damage (%) rate per felling of one tree, 1.77% is relatively small as compared to those widely reported value ranges of 1.64- 2.02%.

Chapter 5 revealed an evidence of forest degradation in selectively logged production forests of Myanmar which are subject to inadequate cutting frequency. We compared stand structure, commercial species composition, and incidence of illegal logging between two compartments with low (LCF; 1 time) and high (HCF; 5 times) cutting frequency over a recent 18 years. Prior to the latest cutting, LCF had 176 trees ha^{-1} with an inverted-J shape distribution of diameter at breast height (DBH), including a substantial amount of teak (*Tectona grandis*) and other commercially important species in each DBH class. HCF prior to the latest cut had only 41 trees ha^{-1} without many commercially important species. At HCF, nearly half the standing trees of various species and size were illegally cut following legal operations; this was for charcoal making in nearby kilns. At LCF, two species, teak and *Xylia xylocarpa*, were cut illegally and sawn for timber on the spot. More extensive and systematic surveys are needed to generalize the findings of forest degradation and illegal logging. However, our study calls for urgent reconsideration of logging practices with high cutting frequency, which can greatly degrade forests with accompanying illegal logging, and for rehabilitating strongly degraded, bamboo-dominated forests. To reduce illegal logging, it would be important to pay more attention on the MSS regulations stating logging road should be destroyed after logging operations.

In *Chapter 6*, the stand structural changes over 5 years after official legal logging operations was investigated using two 1-ha (100 × 100 m) sample plots. For 5 years after logging, the volume of trees with DBH ≥ 20 cm decreased by 46.0% from 121 to 65.1 m^3 ha^{-1}, with a significant loss of the first and second grade species group (teak and *Xylia xylocarpa*) from 48.3 to 6.8 m^3 ha^{-1}. The total tree loss owing to official logging operations, mainly targeting the second and fourth grade species group, was 29.3 m^3 ha^{-1}. The similar level of the total tree loss (28.0 m^3 ha^{-1}) was attributed to illegal logging that targeted the first and second grade species group. The mean annual recruitment rate of 3.1% was larger than the reported values for tropical forests, but there were no and only 1.5 trees ha^{-1} requirements for teak and *X. xylocarpa*, respectively. The mean annual mortality rate of 2.5% was within the values reported in the related literature, and the volume loss from the mortality was relatively similar to the gain from the increment of living trees for all species group. It was concluded that the effects of illegal disturbances for 5-year post-harvest were equivalent to those of the legal disturbances and larger than those of natural change, and are a major cause of the substantial reduction in stocking levels, especially for commercial species.

In overall, the logging damage under the MSS operations at lower level compared to those reported values but depending on the harvesting intensity, and the harvesting intensity regulated only by the minimum diameter cutting limit (MDCL) rule has a tendency toward overexploitation. The logged-over forests with annual growth rate 0.48 cm ha^{-1} is could have a potential to recover. However, illegal disturbances following the legal logging has substantial impact to the growing stocks. In conclusion, human disturbances in terms of illegal logging and repeated legal loggings with repeated construction of forest roads are the most detrimental factors for the degradation of the production forests. It is recommended to limit the harvesting intensity in terms of quantity and size of harvested trees to reduce the impact on residual trees and ground. It is also crucial to decommission the forest roads after the operation to combat illegal logging in the logged over forests.

Chapter 1

General Introduction

1.1. Background

Forests, covering an area of around 4 billion ha or some 30 percent of the earth's land surface (Keenan et al., 2015), are invaluable renewable natural resources and the most productive land-based ecosystems essential to life on earth (UN., 2019). Of these, tropical forests, representing 44% of the total forest areas (FAO., 2015), are the largest in area and irreplaceable source providing ecosystem services and protecting biodiversity for both humans and wildlife (Gibson et al., 2011; Putz et al., 2012). Owing to the vast variations in topography, climatic and soil conditions, tropical forests are extraordinarily diverse and differing in composition and structure. In Asia, the tropical rain forests are centered on the Malay Archipelago but extend from Papua New Guinea north into the continental Asia (Thomas and Baltzer., 2002) encompassing the southeast Asian nations including Myanmar.

Tropical forests, despite their importance, are among the most threatened ecosystems on the earth. Based on the Forest Resources Assessment, the deforestation of tropical forest was about 13 million hectares annually during a period of 2000 to 2010 (FAO., 2011). For the recent decades, to combat the increasing trend of deforestation has been the main global concern and attention of tropical conservation. (Sloan and Sayer., 2015; Asner et al., 2009; Hansen et al., 2013; Malhi et al., 2014). The effort in doing so have had positive outcomes as trends of annual deforestation rate have slowed globally from 0.18 percent in the 1990s to 0.08 percent over the last few decades (FAO., 2015). However, this trend has been outweighed by a strong increase in tropical forest loss in some countries such as Angola, Bolivia, Indonesia, Malaysia and Myanmar (UN., 2019; Burivalova, 2015; Hansen et al., 2013). Particularly, Myanmar, a timber producing country in the southeastern Asia, is ranked third in the list of countries with largest deforested areas 2010-2015 (FAO., 2015). The causes of tropical deforestation are many, varied, complex and often comprise proximate or ultimate causes. In summarizing the causes of tropical forest deforestation, based on 152 sub-national case studies, tropical wood extraction in several forms was singled out as one of the three main proximate causes (Geist and Lambin., 2002). In 2011, annual wood removals amounted to 3.0 billion m^3 globally (FAO., 2016). According to ITTO estimation, at least 350 million ha of tropical forests have been severely damaged, and a further 500 million ha have been degraded due mainly to unsustainable logging (Sasaki et al., 2012). In this regards, tropical selective logging being subjected to at least 20% of the world`s natural tropical forests, about 403 million ha of tropical production forests, has been in the core of global attentions in recent decades. There have been many studies addressing the sustainability of tropical selective logging in terms of carbon retention (Zimmerman and Kormos., 2012; Sasaki et al., 2012; Medjibe et al., 2013; Sist et al., 2014; Griscom et al., 2014; Pearson et al., 2014), biodiversity conservation (Edwards et al., 2012, 2014; Putz et al., 2012; Burivalova et al., 2014) and timber production (John et al., 1996; Pereira et al. 2002; Picard et al., 2012; Sist and Ferreira, 2007).

In effort to improving natural forest management, reduced impact logging (RIL) is implemented globally as a way to balance environmental protection with timber production in the selectively logged production forests in the tropics. Accordingly, great many researches have indicated the effect of tropical selective logging in relation to deforestation and degradation of tropical production forests ,(FAO., 2004; Hawthorne et al., 2011; Sist et al., 2008, Putz et al., 2008a,2008b ; Puodyal et al., 2018) focusing each particular forests: for examples, in the Brazilian Amazon (e.g. Silva et al., 1995); in Uganda (e.g. Chapman & Chapman, 1997); in Indonesia (e.g. Cannon et al., 1994; Sist & Nguyen-The, 2002); in Central Guyana (e.g. ter Steege et al., 1996); in the Western Ghats India (e.g. Pelissier et al., 1998); in Sabah Malaysia (e.g. Pinard & Putz, 1996; Pinard et al., 2000). Amidst such great number of research, unfortunately, there was a dearth of research on the impact of Myanmar selective logging (Pouydal et al., 2014), which has the longest logging history in Southeast Asia (Miettinent et al., 2014). The Brandis selection system, which was introduced in 1856 to suit the tropical mixed deciduous forest in Bago Yoma of Myanmar (Burma), was acknowledged as the first systematic silvicultural management system of the tropics (Zin., 2005). The Brandis selection system, later modified into Myanmar selection system (MSS), has been the principal forest management system in a tropical timber producing nation in the Southeast Asia. Today, about one third of the country land areas, being constituted as permanent forest estate, have been treated striving to sustain under the MSS. It was a tragedy for the tropical Myanmar and the tropical forests as well when the Bago Yoma, the legendary birth place of the MSS, was treated for a 10-year fallow period in 2016 after its reputation and long-standing practices has been tested for 160 years. By large scale analysis through the application of remote sensing data, studies have revealed the occurrence of forest degradation in production forests under the MSS even though deforestation was not occurrence in a large scale (Mon et al., 2010, 2012). This issue of the widespread large scale forest degradation in selectively logged production was also confirmed by large scale systematic forest inventory (Win et al., 2018a, 2018b). While the prevailing issue of deforestation is one of the management problems that needs to be addressed on the political-social level, forest degradation particularly in the production forests is a silvicultural problem that could be addressed with proper technical solutions (Zin., 2005). A handful studies have been attempted to address the factors causing forest degradation in the production forests in Myanmar (Mon et al., 2012, Khai et al., 2016). Indeed, loss of forest resources in terms of forest vegetation, forest areas, decline of forest products and services have been critical development issues which are ranked top priorities of environmental concerns in Myanmar and recommended to address quickly and comprehensively to ensure sustainable economic development (David et al., 2015).

1.2. Research objectives

Tropical selective logging which removes only a small proportion of the targeted commercial trees, by its concept, do not necessarily to relate to degradation. Since recent decades, however it has been a global concern that the tropical selective logging may cause degradation i.e. gradual decrease in stocks of the selectively logged production forests, and then leading to deforestation (Nepstad et al., 1999; Asner et al., 2005: Oliveira et al., 2007). Several studies have been attempting to solve this concern from the aspects of harvesting intensity (Sist et al., 1998, 2003; Parrotta et al., 2002), felling cycle (Kammesheidt et al., 2001; Sist et al., 2003b; van Gardingen et al., 2006), logging damage (John et al., 1996; Picard et al., 2012; Sist and Ferreira, 2007; Khai et al., 2016), recovery and stand dynamics (Silver et al., 1995; Sist and Nguyen The 2002; Cavalho et al., 2004; Dionisio et al., 2018) and illegal logging (Kao et al., 2012; Win et al., 2018) respectively. Conceptually, when the logging disturbance is too high, the remaining forest stocks after selective logging could be unable to recover during the prescribed felling cycle (FC), and then selective logging cause forest degradation and radically alter fundamental ecological process of tree species. Similarly, when the felling cycle is insufficiently long, i.e. repeated logging < FC is implemented, the logged-over forest will be proceeded to similar negative trend. The balance between logging disturbances and recovery of the logged forests during the FC is a key to ensure the long term sustainability of the production forests. In this, the harvesting intensity, which is commonly regulated by one universal rule of minimum diameter cutting limit (MDCL) is the critical factor determining the logging disturbance and subsequent dynamics of the logged forest.

In tropical Myanmar, the total forest cover in 2015 is 29.39 million ha or 42.9% of the country`s territory, in which closed forests and open forest approximately equal in extent (FRA 2015). The total forest cover at this extent was a decrease from 34.42 million ha or 58% of the country territory estimated from the 1989 Landsat TM imageries. Apart from the reduction of total forest cover between the periods, the extent of open forests was sharply increased from 12.32% to almost two folds while closed forest at 46% has dramatically decreased to more than half.

On the other hand, the PFE areas, as of 2018, has further increased to 21 million ha (31% of land area) and it is targeted to increase to 40% of the total land areas under PFE in accordance to Forestry Sector Master Plan (2001-2030). The PFE, distinguished into RFs, PFFs and PAs, denote the legal condition of the lands, which have already been confirmed as forests in accordance with the government records (Aung, 2019). Thus, such increase in the extent of PFE could accordingly be presumed as increase of forests, despite the decreasing trend of forest cover at the country level. Of the PFE, RFs, which are priority areas for timber production, comprise almost 60% of the PFE, as of 2018. These figures indirectly indicated that the prevailing issues to be dealt with regard to the PFE is forest degradation rather than deforestations. Deforestation, which is changes of forest to other land use is indeed the management problems that need to be addressed on the political–social level. The degradation of production forests being subjected to the selective logging called for proper technical solution from the silvicultural aspects.

Traditionally, the MSS with its hundreds years' experiences of continuous timber extractions is considered as sustainable and suitable for maintaining the multi-species, complex natural teak bearing production forests of tropical Myanmar. Notwithstanding the longest logging records, tropical production forests in Myanmar were not in the exception of forest degradation. Concerning with the current problem of forest loss and degradation in Myanmar, studies have claimed that "severe logging" (Bhagwat et al., 2017), "timber extraction" (Lim et al., 2017), "over-exploitation" (Enter et al., 2017) were proximate cause while extraction of only a few commercial species in successive felling cycles was suspected to lead to "creaming" of the forests and resulted in their devaluation through a pronounced decrease in valuable timber species (Zin., 2005) In addition, repeated logging beyond the regulated AAC and prescribed cutting cycle is denounced as causes of forest degradation in Myanmar (Thein et al., 2007). All these aforementioned studies have unanimously highlighted to the issue. However, it remains unknown "why or how does the selectively logged production forests in Myanmar result in forest degradation?". Evidence and field data have been lacking to verify to what extent the MSS practice is responsible for forest degradation particularly in the production forests. Despite its legacy, there is limited empirical study on the impact of logging under MSS, which has been conducted annually over centuries. Deforestation and forest degradation can be caused by a combination of multiple factors from either or/both natural and human disturbances. Several studies have reported that deforestation and degradation of production forests particularly Bago Yoma of Myanmar (Mon et al., 2010,2012; Ne Win et al., 2012; Win et al., 2018a, 2018b).

However, to our knowledge, no study so far has investigated the sustainability of selective logging in Myanmar from the logging disturbances aspect.

Concentrating on the prevailing issue of degradation of productions forests in tropical Myanmar, this study has an overall objective to evaluate the impact of human disturbances and stand dynamics at post-harvest condition in the selectively logged production forests, and to identify possible ways to improve the MSS operations.

Specific objectives are;

1) To evaluate the levels of harvesting intensity and disturbances of Myanmar selective logging operations compared with those reported values for other tropical regions.
2) To evaluate the effect of different felling cycle on stand structure and species composition.
3) To evaluate components of post- harvest stand dynamics from natural occurrences.
4) To evaluate the impacts of human disturbances in term of illegal logging on post-harvest stand dynamics.

1.3. Organization of the dissertation

The dissertation comprises 7 chapters in total, each chapter addressing a particular theme in details. Chapter 1 is an introduction on the background and objectives of this study. Chapter 2 described the overview of selectively logged production forests in Myanmar. Chapter 3 to 7, being the main chapters of the dissertation, are corresponding to each components of the objectives; harvesting intensity, logging disturbance, felling cycle, stand dynamics and illegal logging.

Chapter 3 evaluated the harvesting intensity operated at the minimum diameter cutting limit (MDCL) system, and the level of subsequent logging disturbances in terms of damaged trees (%) and ground disturbance (%) at four different sites under the MSS. Then, this chapter compared the findings with those reported RIL and conventional logging studies across other tropics.

Chapter 4 applied a proposed tree-based approach/model to evaluate logging damage in a tropical mixed deciduous forest in Bago Yoma, Myanmar and compared the cases with semi-evergreen forests of Cambodia.

Chapter 5 comparatively revealed stand structure, commercial species composition, and incidence of illegal logging between two compartments subjected to two different cutting frequency: low harvest (1 time) and high (5 times) cutting frequency over a recent 18 years in the production forests in Bago Yoma, Myanmar.

Chapter 6 exhibited, based on two 1-ha (100 × 100 m) sample plots, components of post-harvest stand dynamics over 5-year period in logged-over forests, highlighting the incidence of illegal logging as one of the factors.

Chapter 7 included general discussion and conclusion that were drawn from the research findings.

Chapter 2

Overview of selectively logged production forests in Myanmar

2.1. Tropical seasonal forests

Tropical moist deciduous forests, frequently also referred to as monsoon forests or tropical seasonal forests, are found mainly in the fringes of tropical rain forests. They are characterized by distinct wet and dry periods (Lamprecht., 1989) and tree species shedding their leaves during the dry season. Typically, tropical seasonal forest extends into southern and southeastern Asia from India, Nepal, Bhutan and Bangladesh to Myanmar, Thailand, Laos, Cambodia and Vietnam to Indonesia. The teak bearing forests of India, Myanmar, Laos and Thailand are a good example of this type. Though tropical moist deciduous forests are of lesser stature than rainforests with a lower biomass, species richness and floristic diversity, they still contain a considerable variety of species and are commercially valuable (Borota., 1991). The evergreens are dominant in some occasions. *Dipterocarpaceae* are less abundant (Whitmore and Burnham., 1984).

The climatic climax of the monsoon tropical climate is tropical moist deciduous forest or tropical seasonal forests such as mixed deciduous forests (Ruangpanit., 1995). The mixed deciduous forests can be found at the elevation range from 50-800 m above mean sea level. The distinct dry season of at least four months is believed to be the limiting factor of the type. (Ruangpanit., 1995). In its composition, this forest type has all deciduous species in a good proportion typically with the closed and high (often reaching >30 m) canopy. Beneath the canopy, the understory is relatively open despite a diverse assemblage of small trees, shrubs, and bamboos forests (Rundel., 2009). In certain localities, one species, *Tectona grandis* (teak) for instance, may become predominant and well adapted (Ruangpanit., 1995). Unlike the evergreen-forest formations, lianas and vascular plant epiphytes are uncommon (Rundel., 1999). Due to the strong seasonality, frequent ground fire is a natural ecological factor in the mixed deciduous forests. The canopy trees exhibit a complete dominance by a deciduous growth habit and, typically shed off leaves in dry season for 4-5 months (Rundel., 2009). Dense local stands of bamboo, mostly deciduous species such as *Dendrocalamus strictus*, *D. membranaceus*, *Bambusa tulda*, *Gigantochloa albociliata*, and *Cephalostachum spergracile,* are often present as indicator species of this forest type (Kermode., 1964; Troup., 1921). Naturally, the mixed deciduous forests usually alternate with the deciduous dipterocarp forest type depending on the mosaic pattern of topography and characteristics of the sites (Ruangpanit., 1995). The historically most significant species in the mixed deciduous forest has been teak, extending natural range from northern India and Myanmar across northern Thailand to northern Lao. Teak distribution characterizes much of the range of mixed deciduous forest (Rundel., 2009). Teak is generally fire resistant at the ground fire and can survive ground fire in the juvenile stage, recovering vegetative by mean of vigorous coppices that sprout from well protected root stumps, when both lighting and weather condition become favorable. Ground fire, which are usual phenomena in seasonal forest types, are in fact maintaining the stock of teak. Otherwise the forest would regress to evergreen climax stage where teak will be unable to perpetuate itself (Ruangpanit., 1995).

In tropical Myanmar, mixed deciduous forests form a wide ring around the central dry zone, over a wide range of annual precipitation as low as 1270 mm to 5080 mm or more. These forest types, which are by far the largest in area and the most important, play an important role as the best quality of teak and other commercially most important timber species grow abundantly in it. Mixed deciduous forests of Bago Yoma is often refereed as 'home of teak'. Based on their common species composition, rainfall distribution and characteristic bamboo species, mixed deciduous forests of Myanmar are classified into three types; Moist upper mixed deciduous forests (MUMD), Dry upper mixed deciduous forests (DUMD) and Lower mixed deciduous forests (LMD)(Kermode.,1964). Teak, pyinkado (*Xylia xylocarpa*) and taukkyant (*Terminalia tomentosa*) are common species found in all three types while other different timber and bamboo species confined to the respective forest types as characterizing species. Teak, which is the most important and characterizing species of mixed deciduous forests, grows well in warm, moist tropical regions with annual rainfall between 1250 mm and 2500 mm and a distinct dry season of 3-5 months.

In Myanmar, the mixed deciduous forest type, which usually has teak as the leading dominant species in the top canopy, is commonly called a teak bearing forest. *Xylia xylocarpa* is the natural associate of Teak in such teak bearing forests and usually intermix with *Lagerstroemia tomentosa, Terminalia alata, T. belerica, Bombax insigne, Pterocarpus macrocarpus, Dalbergia cultrata, D. oliveri, Adina cordifolia, Gmelina arborea, Acacia leucophloea, and Dillenia pentagyna* (Kermode., 1964; Ruangpanit., 1995; Troup., 1921). Some evergreen species such as *Hopea odorata, Shorea asscamica*, *Eugenia* species, *Dipterocarpus alatus, D. turbinatus* are occasionally found in the area, especially along the streams (Ruangpanit., 1995; Kermode., 1964).

2.2. Selective logging under the polycyclic silvicultural system

Natural forest management has been defined as "controlled and regulated harvesting, combined with silvicultural and protective measures, to sustain or increase the commercial value of future stands, all relying on natural regeneration of native species" (Schmidt., 1991). The primary objective of silvicultural intervention in natural forest management is to selectively modify the biotic and/or abiotic environment in the tropical forest to enhance regeneration and growth of a restricted number of tree species (Smith., 1962). Management of natural forest in such a way as to minimize the problems associated with timber extraction is sustainable forest management (Montagnini and Jordan., 2005). The silvicultural systems, which have been applied to manage tropical forests, can be classified into monocyclic and polycyclic system. Monocyclic systems cover all systems that remove all saleable trees at a single operation with the cycle, the length of which more or less equals the maturation age of the trees. The Malayan Uniform System (MUS) designed for natural forests that are relatively uniform and rich in commercial species of the *Dipterocarpaceae* family was a most widely known monocyclic method particularly in the Southeast Asia.

The polycyclic system bases on the repeated removal of selected trees in a continuing series of felling cycles, whose length is less than the time it takes for the trees to mature; usually about half of the time required for the species to reach merchantable size. Under this system, advanced growth is retained and the forest stands result in an uneven-aged structure (Armitage., 1998). It is the most widely applied system for managing natural forests in the tropics. The basic idea is to leave behind an adequate number of residuals stands after logging, which will ensure an economic cut at the end of the cutting cycle and sustainable timber harvest in future. This system offers a flexible, practical, technically and commercially realistic basis for harvesting. At the same time, it influences forest composition and structure in favor of the next crop. Furthermore, polycyclic systems have ecological advantages because they appear to be more natural, the logging damage tends to result in scattered small gaps in the forest canopy.

Tropical forests are a living entity in a state of equilibrium in the growth cycle (Whitmore and Burnham., 1984) and gap phase dynamics has been hypothesized to play an important role. The regeneration is known to be driven by the small –scale disturbance dynamics of randomly occurring canopy gap (Denslow., 1987; Zimmerman and Kormos., 2012). A relatively low impact of tropical selective logging that mimics to the natural gap may serve as the most formative silvicultural operation to be applied during the management cycle in any particular area of tropical forest through its limited effects on the future structure, composition and growth of a forest (Armitage., 1998; Zin., 2005). From the silvicultural point of view, harvesting could be organized as a significant silvicultural intervention and a log production operation by maintaining a level of harvest within the productive capacity of the forests. In practical management, the fundamental complex features of tropical forests usually create a major problem while the structural and compositional simplification and refinement of these forest systems are also necessary for an efficient wood production, where a very few commercial timber species are sparely present (Zin., 2005). Unfortunately, in spite of the intensive efforts of many forest services, the results of these selection systems following the polycyclic system have often not been very encouraging. In fact, there is no single silvicultural system that can be blindly applied in every forest nor universally valid silvicultural recipes. All systems always have to be adapted to local conditions when they are applied in practice. In tropical Myanmar, a selective logging known as "Brandis Selection System" being based on a yield regulation system and applicable to the moist deciduous forests of Myanmar was introduced in 1856 (Blandford, 1956). That first effort to bring the natural tropical forests under conditions of scientific management was the basis for future management development in the tropical world (Zin.,2005). Today, after the exercise of 160 years of application, the MSS has been modified towards bringing conservative silviculture into harmony with profitable exploitation on a sustainable basis (Tint., 2014).

2.3. Status of natural forests and management in Myanmar

Myanmar, a tropical country in the continental South East Asia, is one of the biodiversity hotspots (Krupnick et al., 2003; Myers et al., 2000). Owing to the diverse climatic, topographic and a wide range of latitudes, the forest flora of Myanmar ranges from sub-alpine forests in the far north through extensive tropical deciduous forests and dry forests surrounding the central Myanmar to tropical rain forests including mangroves in the southern part. Among plant species about 11,800 recorded so far from natural forest resources, 1071 are endemic (NABSAP, 2015). Out of 2088 species of big and small trees, 85 species have been recognized and accepted as producing multiple–used timber of good quality. Particularly, teak native to Myanmar is regarded worldwide as one of the most valuable premier woods. Forest area of Myanmar estimated by forest types and function are mixed deciduous forests including teak (38% of the total forested area); hill and mountain evergreen forests (25%), tropical evergreen forest (16%), dry forests (10%), deciduous dipterocarp forests (5%); and tidal and swamp forests (4%) respectively. Of these forests, the most extensive and economically most important forest types are tropical mixed deciduous forests because teak, *Xylia xylocarpa*, *Pterocarpa macrocarpus* and other commercial species are usually associated with this forest type. No less important are the *Dipterocarps* forests which are confined to the tropical evergreen forests and deciduous forests.

In Myanmar, the forests are State-owned in accordance with the forest law and are categorized legally as Reserved Forest (RF), Protected Public Forest (PPF) and Protected Area Systems

(PAs). All these forests: RF, PPF and PAs amounted 21 million ha area (~31% of the country`s area) as of 2018, are recognized as Permanent Forest Estate (PFE). The forest policy has stipulated to have 40% of the country`s area under PFE by 2030. Of the PFE, majority areas mostly from the RFs are designated as production forests and subject to selective logging under the MSS. Again, the majority of production forests (86% of the total) are stretching over the tropical mixed deciduous forest types while the rest are found in evergreen forests. Sub-tropical and temperate forests, which are found in hill and mountains, have often been outside the range of forestry activities.

From the ecological aspect, the distribution of teak, a light demanding species (Troup., 1921), characterizes much of the range of mixed deciduous forests in associated with *Xylia xylocarpa*, a shade bearing species, and bamboo such as *Bambusa polymorpha*, *Cephalostachum pergracile*, and *Dendroclamus strictus* as indicator species in the intermediate layers (Kermode., 1964). Teak as the predominant species occurs naturally with varying degree of stocking and quality. The proportion of teak, however, rarely exceed 20% of the total stock (Tint., 2014) while other species selfdom exceeds 3% (Watson., 1923) in the natural forests.

In fact, teak always play a typical role throughout the history of Myanmar forestry. Forest management in Myanmar has been natural forest management founded on the concept of sustain yield and primarily initiated with teak. Since even during the era of ancient Myanmar kings, teak trees was declared as royal property and a complex system was formulated to maximize revenue and control (Brandis., 1896; Gyi and Tint.,1998), and in today, in accord article 8(a) of the Forest Law, a standing teak tree wherever situated in the State is owned by the State. When the scientific forest management was officially started in 1856 with the introduction of the so-called Brandis management system (Dah, 2004), teak was the only commercial species at that time. The management of natural forest was therefore oriented towards the sustainable production of teak, and designed to favour teak regenerations i.e. improvement felling and thinning of natural congested stands. In later years, management of other commercially important species was also considered, and accordingly, the original Brandis Selection System was modified into the Burma Selection System in 1920. This system, known gradually as the Myanmar Selection System (MSS) has been the principle forest management in tropical Myanmar (Dah, 2004; Gyi and Tint., 1998; Zin., 2005).

In its principle, the MSS can be said founded on three main components; adoption of 30 years cutting cycle, prescription the minimum diameter cutting limit (MDCL) of harvesting trees and fixing of annual allowable cuts (AACs) for timber harvesting. For timber harvesting purpose, the production forests are organized into different working circles based on the nature and form of forest products and accessibility. The working circles consist of a group of RF, which is further divided into felling series for the convenience of working according to the drainage and the geographic situations. As MSS adopts a 30-year felling cycle, a felling series is then divided into 30 blocks of approximately equal yield capacity. Each year, selection felling is carried out in one of these blocks and the whole forest under a particular felling series is therefore worked over a felling cycle. All marketable trees > MDCL in the planned block are selected for harvesting. For teak, the MDCL varies with the type and status of the forests. In good (moist) teak forests, the MDCL is 73 cm DBH and in poor (dry) teak forests 63 cm DBH (Dah, 2004). The fixed MDCL for other hardwoods varies, mostly 58- 78 cm with the species depending on the growth rate and size at maturity. If seed-bearers are scarce, a few high quality stems above the exploitable size may be retained as seed trees. Trees left standing at the time of the selection are recorded, down to 39 cm DBH for teak, and 10 cm DBH below the exploitable size for other hardwood species. This provides a reliable basis for calculating the future yield. Trees of exploitable sizes are selectively marked within the bound of AACs calculated for each felling series based on the principle of sustained yield management.

In the standard practice, mature teak trees selected for harvesting are normally girdled and left standing for three years before being felled and extracted. This is to season the timber and make it floatable as logs are normally transported by floating down the streams and rivers. Improvement Felling (IF) and thinning in very dense young stands are carried out at the time of girdling to favour teak. Annual yield known as AAC is estimated, based on the basis data obtaining from 100 % enumeration and forest inventory, by the formulae;

$$\mathrm{AAC} = \mathrm{ARR} + \frac{\left[WS - \left(\frac{1}{2}\,\mathrm{FC} \times \mathrm{ARR}\right)\right]}{\mathrm{LP}}$$

where, AAC Annual allowable cut

ARR Annual rate of recruitment

= Number of trees within 1feet girth (10 cm DBH) class below the MDCL divided by time of passage (30 years)

WS Existing working stock = number of trees of above MDCL

FC Felling cycle (30 years)

LP Decide period to liquidate original WS (usually 60 years)

AAC at each forest management unit level has been periodically revised as necessary depending on new data. At the country scale, estimated AAC of teak and non-teak hardwood in 1995 were 124,213 teak trees and 1,795,424 non-teak hardwood trees. These AAC values however decreased to 48,897 for teak and 817,343 trees for hardwood species in 2016, and further 19,210 for teak and 593,330 for non-teak hardwood trees, respectively (Source: FD, 2017). The MSS was believed to be an excellent one and the only feasible way to deal with multispecies, complex natural forests of the country (Dah., 2004), and it has become discernable that the sustainability of the forest resources is under serious threats. The drastic decrease of AAC tree indicated that the productivity of forest has decreased both in quality and quantity. Especially, the decrease in AAC for teak is significant.

2.4. Timber extraction in Myanmar

The extraction of teak through girdling method was recorded since the pre-colonial period in 1824 (Kyaw., 2004). Putting aside the depletion of teak forests in Mawlamyaing in southern Myanmar under the *laissez-faire* condition by private firm, the commercial logging with scientific forestry began with the arrival of botanist-turned- forester Dietrich Brandis in the middle of the 19th century (Bryant., 1996), along with the declaration of all forest as the state property and creation of reserved forests (RF) in accordance with the Burma Forest Act (1881). Throughout the colonial era, teak extraction for export was the official attention (Bryant., 1996) and logging was opened to private enterprise in the lower part of Myanmar (Kyaw., 2004). When the Ministry of Forestry (MoF) has established in 1923, timber extraction by private were under the control of MoF. Until the World War II, British private companies were engaged in teak loggings.

After 1948 independence, two governmental institutions under the MoF have been involved in the forestry sector: Forest Department (FD) which is responsible for the protection, conservation and management of forest resources and the State Timber Board (STB) established to undertake the commercial exploitation, processing and marketing of teakwood in 1948. Established private national timber businessmen were granted licenses to continue extraction of non-teak hardwoods under contracts. (Zaw., 2004). Hardwood marketing was nationalized in 1963 and all private-owned sawmills were also brought under the State control in 1965 under the socialist economic system. In 1974, the STB was reorganized under the socialist economy and renamed Timber Corporation (TC), and again in 1989, with reformed market-oriented economy by the Junta, the TC was changed to the Myanmar Timber Enterprise (MTE). To date, the MTE is a sole state-owned economic enterprise which has legal right of harvest, process and market in Myanmar.

For timber harvesting under the MSS, selection felling (SF) marking of harvesting tree, girdling of teak tree are conducted by FD based on the AAC prescribed in accordance with the District Forest Management Plan. Each year FD and MTE have to perform together matters such as teak trees to be girdled, teak trees to be green felled, non-teak hardwoods to be selectively marked for felling. All this information with respective trees location maps is handed over to MTE for timber harvesting operation.

Seasonal extraction operation of the MTE usually commences in June each year after the first shower of the rain. In directional felling, the felling of marked tree is very important as not only to damage the felled tree itself but also the nearby trees, saplings and advance growth. Good felling direction is towards or away an extraction direction forming an angle with the extraction direction of 30-50 degree (MoF, 2000). In practice, it is common to fell according to the natural direction of fall. A combination of elephant power and mechanical power is employed for extraction work. Stumping, skidding of logs away from the stump of the fell tree to the log landing (measuring point) where logs are temporarily collected is done usually by elephant power. When mechanical power is aided in logging, elephants assist to drag logs from the stump to wider drag paths or clearing just outside the extracting areas. Further hauling or skidding is done by skidders up to the log landings/ measuring points or forest car base. Then loading is done by wheel loaders onto timber hauling trucks.

Forest roads mostly are seasonal and feeder road were constructed for purpose of log transportation. Forest road construction starts at the end of rainy season or when forest soil is hardened around November in each year. Bulldozers and backhoes are usually employed in this operation. Whereas favourable old forest roads were renovated and used rather than construction of a new forest road. Though the practical implementation is not enforced strictly, the logging activities are guided by the national code of forest harvesting practices (MoF, 2000) which gives detail guidelines for activities such as the alignment and construction of extraction roads, skid trails and stream crossings; the marking of tree positions on a map; climber cutting before felling; and the directional felling of selectively marked trees. Logging is to be excluded in slope steeper than 35° and 10 meter on each side of the streams is demarcated as buffer zone in accordance with the National Code of Forest Harvesting Practice.

Basically, MSS has been the only system consistently practiced in managing the forests. Timber harvestings regimes under the MSS involve harvesting of commercial tree species attaining the MDCL at breast height, with prescriptions. Such regimes, from silvicultural aspects, intended to allow the residual stands to regenerate and revert to mature stands embraced as suitable approaches to protect forest integrity while allowing continues yields. Nevertheless, there were certain deviations of the employment of MSS from its standard prescriptions, throughout decades. In its initial era, the logging targeted only on teak. During those time, mature teak trees were selected to be girdled and left standing for three years prior to felling. Girdling teak was a must do operation because the only practical method during those time was dragging of logs by elephants or buffalo to the nearest watercourse and floated down during the rains into the streams and rivers to the main port. This traditional practice of teak girdling was gradually stopped and came to an end in 2005 as green teak extraction has started in some accessible areas since 1980 up to present (Myint., 2012; Kyaw., 2004).

Natural forests are managed according to the prescriptions of the District Forest Management Plan under which working circles are formed on the basis of the management objectives, nature and form of the forest produce required. For timber production, Teak Selection Working Circle (TSWC) which includes all teak bearing forest, Hardwood Supply Working Cycle (HSWC) and Local Supply Working Circle (LSWC). In general, logging for teak and non-teak hardwood were, separate operations. Occasionally, however, TSWS and HSWC were overlap when non-teak hardwoods were also extracted in an area (Dah., 1999). When the new timber extraction approach was introduced in 1970s, the TSWS and HSWC were amalgamated into Production Working Cycle. One of the main deviation from the MSS prescriptions was, apart from the green teak extraction, the MDCL for all teak bearing forests was fixed at 63 cm DBH, as a trial measure to be practiced for some years. Besides*, Xylia xylocarpa* and *Dipterocarpus* species (*Kanyin*) of the two main commercial hard woods were extracted at 10 cm DBH (1 foot) down to its original MDCL.

There was once a term "Modified Procedure System (MP)" used for logging concession predominately allocated by and to local elites in non-state areas. Under this MP, the private mostly local ethnic leaders were allowed to extract timbers with some exemptions in the exploiting sizes; for teak, the first log from bole part should be ≥ 48 cm diameter while the top bole should be ≥39 cm diameter. Likewise, for non-teak hardwood is permitted to extract at 10 cm in diameter down to the normal prescribed MDCL.

Freight on Board (FOB) system by sub-contractor was once granted permission for extraction of non-teak hardwood on behalf of the MTE especially when the harvesting quota was high. Under the FOB system, all of the harvesting expenditures had to be invested by the company themselves. The FOB system was terminated after improper conducts were found. The company involvement, however was continued in different aspects in the timber extraction sector. According to the Extractive Industries Transparency Initiative (EITI) report, companies were involved in extraction of both teak and hardwood; for instances, in 2014-2015 fiscal year the MTE extract 54% and 30% of teak and non-teak hardwood, the company extracted 46% and 70%, respectively. Prior to the exercise of 2016 logging ban policy, the MTE extracted 34% of teak 31% of non-teak while the companies sector extracted 66% and 69% respectively in 2015-2016.

Since 2014-2015, the timber extraction has reduced to be within the limit of the AAC prescriptions. The annual operational plan during 2014 was 60,000 tonne of teak, which was more than six folds lower than the 2011 plan (371,000 tonne), according to the MTE data. Likewise, non-teak hardwoods extraction plan in 2014 was 670,000 tonnes as compared to 1,789,400 tonnes of 2011 plan (Enter et al., 2017). In 2016, logging was temporarily banned in a country scale, and at the same time the first steps to reduce the AAC has initiated (Enter et al., 2017). When the timber extraction has resumed in 2017-18, after one year logging ban, the MTE declared that all logging operations will be on the power of itself. Due to incomplete manpower and facilities, however, the MTE has to use external power, for instances, chain saw gangs for tree felling operations, private owned elephants for log skidding operation, transportation of logs etc.

Chapter 3

Harvesting intensity and disturbance to residual trees and ground under Myanmar selective logging; Comparison of four sites

3.1. Introduction

The potential impacts of deforestation and forest degradation in the tropics on greenhouse gas emission and climate change have become increasingly apparent in this century. Therefore, the sustainability of tropical forests, which account for about 44% of forests globally (Keenan et al., 2015), has attracted global concern. This has been manifested in the recognition of the sustainable management of forests (SFM) along with conservation of forest carbon stocks and enhancement of forest carbon stocks in existing forests in developing countries under the REDD+ scheme of the United Nations Framework Convention on Climate Change. Given that 20% of natural tropical forests are subject to selective logging (Blaser et al., 2011), improved forest management with carbon retention while maintaining timber production has become a critical topic (Griscom et al., 2019; Sasaki et al., 2016; Mazzei et al., 2010; Putz et al., 2008), especially for timber-producing countries where forestry exports are a vital source of national income.

Minimizing the impacts of selective logging on residual trees and the ground is one of the most fundamental elements to improve selective logging operations (John et al., 1996; Sist et al., 2007; Picard et al., 2012; Pinard and Putz 1996). Thus, reduced-impact logging (RIL) has been implemented globally (FAO., 2004) and is widely recognized as a key component of sustainable timber harvesting (Putz et al., 2008). Several studies have reported that RIL techniques can reduce the overall collateral damage to a residual stand by 50% or more (Putz et al., 2008; Johns et al., 1996; Sist et al., 1998), and thereby retain biodiversity, carbon, and associated ecosystem functions (Berry et al., 2010; Burivalova et al., 2014; Edwards et al., 2014). However, the nature and extent of those reported findings are often site-specific and biased to the distinctive features of each tropical region (Poudyal et al., 2018). Studies on the impacts of selective logging are largely biased toward specific countries, such as Brazil, Malaysia, and Indonesia, where tropical rainforests are dominant, while fewer have focused on countries such as Myanmar, Cambodia, and Vietnam, where tropical seasonal forests are dominant (Hari Poudyal et al., 2018).

Myanmar in southeast Asia is the only country in which deciduous forests with a large proportion of natural teak are designated as production forests. These production forests have been subject to the Myanmar selection system (MSS) since 1856 (Dah et al., 2004; Puettmann et al., 2015), and have formerly been the main provider of premier teak worldwide. Until recently, the export timber trade, which represents a key source of export revenue, has played a decisive role in determining forest sector policy, and to this day it exerts influence on overall national politics (Springate-Baginski et al., 2014). The MSS involves the adoption of a 30-year felling cycle, the prescription of exploitable trees by MDCL, the use of elephants for skidding, and the estimation of AAC from the nationwide inventory data. The principal concept is to maintain sustained yields without depleting the resource base and causing minimal environmental degradation.

Considering its principal concept and its 100 years of use in timber harvesting, the MSS seems to be a form of SFM that is feasible for use in complex and multi-species natural forests. However, based on remote sensing studies (Mon et al., 2010; Mon et al., 2012), forest degradation has occurred in selectively logged production forests in Myanmar. Based on large-scale forest inventory data, (Win et al., 2018a) confirmed the existence of widespread large-scale forest degradation in logged forests. After notification of this forest degradation status, the forest policy in Myanmar was updated to include a logging ban for 2016–2017 over the country and for 10 years in the Bago Mountain Range (the so-called "Bago Yoma"), the site of the main production forests in lower central Myanmar. Moreover, when timber harvesting resumed in 2017–2018, the annual harvesting plan was set to harvest only 55% and 33% of the fixed annual yield for teak and non-teak hardwood, respectively. Even though it is planned to reduce the amount harvested at national and regional scales, it is still unknown to what extent MSS operations are responsible for degradation of the production forests, or how to improve MSS operations. (Mon et al., 2012) reported that MSS does not cause forest degradation provided that the logging intensity is below the prescribed annual yield. If it is above that intensity, the likelihood of forest degradation increases markedly. (Khai et al.,2016) reported that logging damages residual trees and soils at a harvesting intensity of 4.6 trees ha^{-1} under the MSS. This was among the lowest values reported worldwide, and suggested that directional felling towards bamboo and the use of elephants for skidding contributed to the lowest level of disturbance of MSS. However, those results came from only one study site, and they did not compare different harvesting intensities. It is known that logging damage increases with increasing harvesting intensity, so it is important to evaluate logging damage in various sites under different harvesting intensities (Sist et al., 1998).

The objectives of this study were to evaluate the disturbance levels of MSS operations compared with those reported for other countries, and to identify possible ways to improve MSS operations.

More specifically, we used data from four study sites with a total of survey area of 36 ha to test the following working hypotheses on disturbance caused by MSS that arose from a single case study (Khai et al., 2016):

1) The harvesting intensity in MSS is relatively low;
2) Felling damage and ground disturbance in MSS are at the lowest level;
3) Directional felling towards bamboo is effective to reduce residual tree damage; and
4) Elephant skidding is effective to reduce ground disturbance.

3.2. Materials and Methods

3.2.1. Study site

In Myanmar, tropical mixed deciduous forests are distributed extensively between roughly 16° to 26°N, and represent the largest and the most ecologically and economically important forest type. These forests contain production forests that have been subject to commercial timber extraction for decades. Our study with the overall objective to evaluate logging damage was conducted at four different sites in the production forests; one in Bago District in lower central Myanmar, and the other three in Katha District in upper central Myanmar (Figure 3.1, Table 3.1).

Table 3.1 Description of the study site

	Site1	Site2	Site3	Site4
Location				
District	Bago	Katha	Katha	Katha
Township	Bago	Kawlin	Kawlin	Pinlebu
Researved Forest	South Zamaye	Pyinde	Pyinde	Gaingshi
Latitude	17°50′48″N	23°53′30″N	23°53′20″N	24°02′52″N
Longtitude	96°07′19″E	95°57′40″E	95°58′30″E	95°07′12″E
Climate				
Annual precipatation	2500 mm	1700 mm	1700 mm	2000 mm
Mean temperature	27 °C	25 °C	25 °C	25 °C
Compartment				
ID	93	45	46	196
Area	740 ha	176 ha	212 ha	610 ha
Soil type	Fluvisols	Ferrasols	Ferrasols	Arenosols
Terrain	Steep	Gentle slope	Gentle slope	Steep
Year of logging	2012	2017	2017	2017

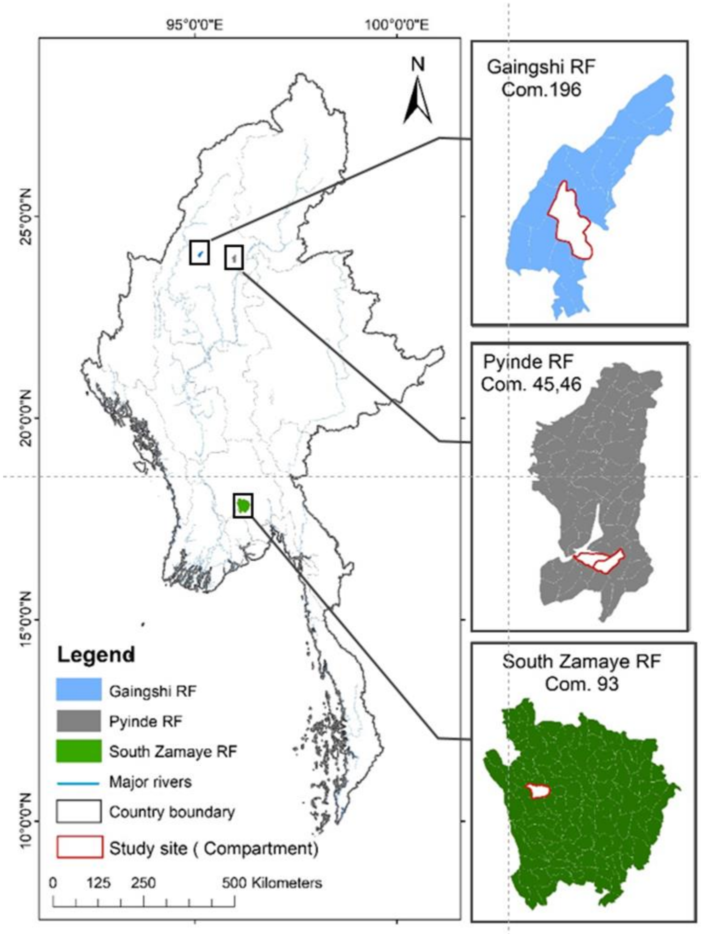


Figure 3.1. Location of study area

Myanmar has a typical tropical monsoon climate with two distinct seasons; a wet period from the end of May through November, and a dry period from November through May. The rainy season normally starts in June with heavy rainfall often occurring until October. The major natural vegetation at the study sites is typical moist upper mixed deciduous forest, which is the classic habitat for teak (*Tectona grandis*) and other valuable timber species. In the South Zamaye Reserved forest (RF) (Site 1) in the Bago District, *T. grandis, Xylia xylocarpa*, and *Lagerstroemia speciosa* are the dominant species with *Bambusa polymorpha* and *Cephalostachyum pergracile* (Forest Department, 2010, 2015a) In Compartments 45 and 46 of the Pyinde RF (Site 2 and Site 3) and the Gaingshi RF (Site 4) in Katha District, *T. grandis, X. xylocarpa* and dipterocarp species grow extensively in association with *Dendrocalamus brandisii* and *Dendrocalamus strictus* (Forest Department 2015b).

3.2.2. Timber harvesting at study areas

At Site 1 in Bago Yoma, the timber harvesting conducted in 2012 was the first official timber harvesting since 1995. Although there was no timber extraction record available for the period prior to 1995, the existing old stumps indicated that timber harvesting was conducted at the site at least twice before that year. Very old and decayed teak stumps were distinguishable by their texture, size (> 73 cm diameter), and low height (approx. 0.2 m), consistent with the rules for felling teak. Other non-teak hardwood stumps were not as old as the teak stumps but were larger and taller, and were believed to be remnants of partial extraction conducted prior to the construction of the irrigation dam around the 1990s. Due to this construction, some parts of the compartment are still submerged in water. In total, 1,071 trees were marked as hardwood selected trees by the Myanmar Forest Department for timber harvesting in 2012 from Compartment 93. A private subcontracting agent under the government-side Myanmar Timber Enterprise performed the timber extraction. A log export ban and logging ban were imposed in Myanmar in 2014 and 2016, respectively, and so the whole Bago Yoma including our study site (Site 1) entered a 10-year fallow period commencing from 2016.

Since timber harvesting re-commenced in 2017, the Katha District in upper central Myanmar has become the main timber extraction region in Myanmar. Out of a total harvesting plan of some 191,500 trees (365,000 ton), about 12% was planned to be extracted from the Katha District. In the Pyinde RF in the Katha District, 168 and 332 hardwood trees were targeted for extraction from Compartments 45 (Site 2) and 46 (Site 3), respectively. In the recent 10-year period, no timber extractions were recorded at the two sites. However, we encountered a few very old stumps of teak and hardwood at Site 3 indicative of a past logging record. Also, according to the locals, laterite rocks had been extracted from some parts of Site 2 during the construction of the Shwe Bo – Myitkyina road, which passes through the RF.

Under the MSS, timber extraction plans for teak and non-teak hardwood are usually formulated separately as the relevant rules and regulations to be followed in logging operations are different. At Site 4, Compartment 196 of the Gaingshi RF, 1403 teak trees and 3208 hardwood trees were targeted for extraction in 2017, and simultaneous extraction teak and non-teak hardwood trees was conducted at this site. At this site, we encountered a few giant old stumps of hardwood trees, mainly dipterocarp species. A private company was granted permission for partial extraction during

2010–2011. Other teak stumps with various sizes that we encountered were illegally cut trees during partial hardwood extraction.

3.2.3. Logging operations

The government-side Myanmar Timber Enterprise was responsible for the timber extraction, which mainly involves operations of tree felling, log stumping and skidding, logging road construction, and log transportation. At Site 1, tree felling operations were conducted during December 2012, followed by log stumping and skidding, and the whole logging operation including log transportation was completed in March, 2013. At the other three sites in the Katha District, tree felling operations commenced in July 2017, during the rainy season. The workload was lower at Sites 2 and 3 than at Site 4, so all the logging operations at Sites 2 and 3 were completed before December. At Site 4, the logging operations continued until February 2018.

Tree-felling teams were composed of one chainsaw and two workers, mostly ethnic Karen nationalities who have been engaged in timber extraction for many years as their traditional profession. The MSS guidelines suggest that trees should be felled along a contour line near the ground and/or towards bamboo clumps, rather than towards residual commercial trees. Skidding of logs away from felled stumps to a log landing, where logs were temporarily collected, was achieved mainly using elephant power. At Sites 2 and 4, however, some trees were too big for transport by elephants, so a bulldozer (D65) was used for skidding. Forest roads for log transportation were constructed by a bulldozer (D65) after the end of the rainy season, generally after November when the soil had hardened.

3.2.4. Sampling plots

For each of four sites, we established a 9-ha rectangular (300 m × 300 m) plot with nine 1-ha subplots. An intensive forest inventory was conducted at two of the subplots (Subplots A and B) (Figure 3.2). The logging areas at Sites 1 and 4 were relatively large compartments situated in deep forest. For these two sites, we subjectively selected the base point of the sampling plot by attempting to find a location representative of a production stand so that the plots included some of the trees marked for harvesting, while avoiding inaccessible areas that were too steep and/or lacked commercial species.

The other two sites, Sites 2 and 3, were situated adjacent to each other in the Pyinde RF, and were much smaller compartments that were located in easily accessible areas. There is a boundary at the tri-junction of Compartments 44, 45, and 46 of the Pyinde RF. From that tri-junction post, we measured 100 m south toward Compartment 46 and made the base point for Site 3. To establish the basepoint of Site 2, where only 168 trees were marked for felling within the 176-ha area of the compartment, we simply selected the unseen marked tree No. 100 as the base point. Then, from each basepoint, the base line and cross lines of each 9-ha plot were laid out in north–south and east–west directions.

In Subplots A and B among the nine subplots (Figure 3.2), all trees with DBH ≥10 cm and all the bamboo clumps were individually numbered and tagged prior to tree felling operations. Species of trees and bamboos were identified with the aid of local foresters and field staff of the extraction agency, and then confirmed against checklists. Tree damage evaluation was conducted in Subplots A and B while the area of ground disturbed by logging operations was measured in the 9-ha plots.

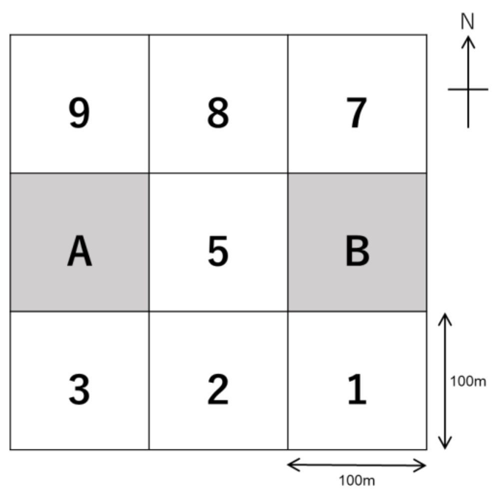


Figure 3.2. Layout of nine 1-ha subplots

3.2.5. Minimum diameter cutting limit for commercial species

In MSS, tree species are classified into six commercial groups; teak and non-teak hardwoods (Groups I–V). Group I species are commercially the most important as the value decreases from Group I through IV, while Group V are lesser-used species (LUS). The MDCL varies with species and also with topographical region. The MDCL for the hardwood species in Bago District (Site 1) ranges from 58 to 78 cm DBH, and for major commercial species at Site 1 (*X. xylocarpa, L. speciosa* and *T. tomentosa*) the MDCL is prescribed at 68 cm DBH (Forest Department, 2010). The MDCL for teak in the Katha District (Sites 2, 3, and 4) is 63 cm DBH while it ranges from 48 to 78 cm DBH for the other hardwood species. The MDCL for relatively big trees such as Dipterocarps is prescribed at 78 cm DBH. For most species such as *Dipterocarpus tuberculatus, X. xylocarpa*, and *T. tomentosa*, the MDCL is set at 68 cm DBH while it is 58 cm DBH for *Pentacme siamensis* (Forest Department, 2015b).

3.2.6. Data analysis

The stand structure prior to tree felling operations was evaluated in two 1-ha Subplots A and B at each study site. The size and species of harvested trees was measured in the 9-ha plots. Immediately after tree felling operations, the frequency of various damage levels due to tree felling was evaluated in Subplots A and B using established methods reported in the literature (Johns et al., 1996; Medjibe et al., 2011). In this method, damage to crowns, boles, and roots was ranked on a scale of minor, moderate, or severe. Crown damage was deemed severe if >66% of the crown was lost, moderate for 33%–66% loss, and minor for <33% loss. Bole damage was recorded as severe when the bole was smashed, uprooted, or broken. Bole damage was assessed as moderate if >100 cm^2 bark was removed, and as minor for less than that value. Root damage was classified as severe if >10% of the surface root was damaged, and as minor for less than that value. Crown, bole, and root damage were attributed to felling and/or skidding.

About 3 months after tree felling and elephant skidding operations were completed, the extent of the soil surface area disturbed by elephant skidding and construction of log landings and forest roads was measured in the 9-ha plots. We defined ground disturbed area (GDA) as top soil that was bladed off or removed.

To analyze the relationships between harvesting intensity (trees ha^{-1}) and rates of damage to residual trees and bamboo clumps (% in number), we counted only the fell-in harvested trees (i.e. excluding fell-out trees) within the eight 1-ha subplots A and B. A total of 49 standing trees were harvested from the four sites. Among them, six harvested trees (one tree from Site 1B, three from Site 2A, and one each from Sites 4A and 4B) had fallen outside the subplots, causing no damage to residual trees in the subplots. Two harvested trees standing outside the subplots had fallen into subplots at Sites 2B and 3B, causing substantial damage there. These two felled-in harvested trees were included but the six felled-out harvested trees were excluded, yielding a total of 45 felled-in trees from eight 1-ha plots for analysis of the relationships between felling damage rate and harvesting intensity.

3.2.7. Comparison with other tropical studies

We compared our results for logging damage with those published in studies conducted in other tropical regions. First, we compared the relationship between harvesting intensity and felling damage rate (%) with the values reported in other studies. For this, the values from this study were based on each of the 1-ha subplots A and B (n=8). For comparison, we selected data from three studies covering a wide range of harvesting intensities (Sist et al., 1998; Sist et al., 2003a; Van Der Hout, 2000) among a total of six studies, which were compiled by (Chheng et al., 2015) and also used by (Khai et al., 2016). We also compared felling damage rates between residual trees and bamboo clumps. We used a linear regression model to express the relationship between felling damage rate (%) and harvesting intensity (trees ha^{-1}) and to check whether the relationship with tree damage determined in this study was significantly different from those detected in the other three studies and the relationship with bamboo clump damage.

Second, we compared our results for ground disturbance (%) resulting from skid trails, log landings, and forest road construction with those reported in published studies on RIL and conventional logging (CON) in other countries. Among a number of studies focusing on ground disturbance by tropical selective logging, we selected studies that had the same variables as our study: that is, harvesting intensity, and percentage of area disturbed by forest roads, log landings, and skid trails. We excluded studies that provided a single variable (e.g. logging roads or skid trails only). We compared the results of our study with those of the following seven published studies: (Asner et al., 2004; Feldpausch et al., 2005; Gideon Neba et al., 2014; Jackson et al., 2002; Johns et al., 1996; Medjibe et al., 2013, 2011; Pereira et al., 2002). In this comparison, the variables of disturbance rate and harvesting intensity were calculated on the basis of the 9-ha plot (n=4). We used a linear regression model to express the relationship between ground disturbance rate (%) and harvesting intensity (trees ha-1) and to check whether this relationship detected in this study on MSS was significantly different from the relationships detected for RIL and CON in the other seven studies.

3.3. Results

3.3.1. Forest structure pre-harvest

Before logging, there were variations in stand structure among the 8 A and B subplots, ranging from 85 to 270 trees ha-1 for the density of trees with DBH ≥10 cm and from 9.8 to 3.8 m^2 ha^{-1} for tree basal area (Table 3.2). The number of bamboo clumps ranged from 56 to 258 clumps ha^{-1} (Table 3.2). The DBH distribution before logging showed an inverse -J shape at all sites (Figure

3.3). Site 3 had few big trees larger than 50 cm DBH, while Site 4 had many large trees, even though it had a relatively small total number of trees, especially in the smaller DBH classes (Figure 3.3).

Table 3.2. General statistics of subplots A and B in four sites

Site	Site 1		Site 2		Site 3		Site 4	
Subplot	A	B	A	B	A	B	A	B
Tree density (trees ha^{-1})	201	151	236	161	270	239	158	85
Tree DBH (mean±SD, cm)	31.4±21.8	24.4±15.2	24.3±17.8	30.7±14.8	22.2±11.2	28.6±14.1	30.2±20.5	43.3±37.3
Tree BA (m^2 ha^{-1})	23.1	9.8	16.8	14.7	13.0	19.0	16.5	21.7
Tree species richness	43	41	45	48	44	48	45	27
Bamboo clump density (clumps ha^{-1})	258	261	56	93	56	96	59	145
Bamboo clump BA (m^2 ha^{-1})	11.6	10.0	1.2	0.7	0.6	1.0	1.3	3.7
Bamboo species richness	2	3	2	3	2	3	3	2
Harvesting intensity (ha^{-1})	8	2	10	3	3	0	7	16
Influential harvesting intensity (ha^{-1})*	8	1	7	4	3	1	6	15
Tree damage rate (%)	8.0	0.0	5.9	5.0	0.7	0.4	7.6	25.9
Bamboo-clump damage rate (%)	9.3	0.8	3.6	2.2	0.0	0.0	15.3	23.4

*The number of harvested trees (ha^{-1}) excluding trees that had existed within the subplot but were felled down outward the subplot and including trees that had existed outside the subplot but were felled into the subplot.

3.3.2. Harvesting intensity and species

Among the 36 1-ha subplots, the harvesting intensity varied from 0 to 18 trees ha^{-1} (143.7 m^3 ha^{-1}) with a mean value of 5.2 trees ha^{-1} (39.9 m^3 ha^{-1}) (Table 3). At Sites 3 and 4, the average harvesting intensity ranged from 1.4 to 10.3 trees ha^{-1} and from 7.7 to 98.4 m^3 ha^{-1}, respectively (Table 3.3). The average DBH of harvested trees was lowest (65.2 cm) at Site 3 and highest (96.1 cm) at Site 4 (Figure 3.3).

Among 13 harvested species within a total area of 36 ha, the dominant species in terms of stem volume was *X. xylocarpa* (Group I), followed by *Dipterocarpaceae* species (Group II) and *T. tomentosa* (Group III) (Figure 3.4). These three species were also the dominant species harvested at Site 4, but *X. xylocarpa* and *Dipterocarpaceae* species were dominant only at Sites 1 and 2, and not at Site 4 (Figure 3.4). Harvesting of teak was allowed only at Site 4.

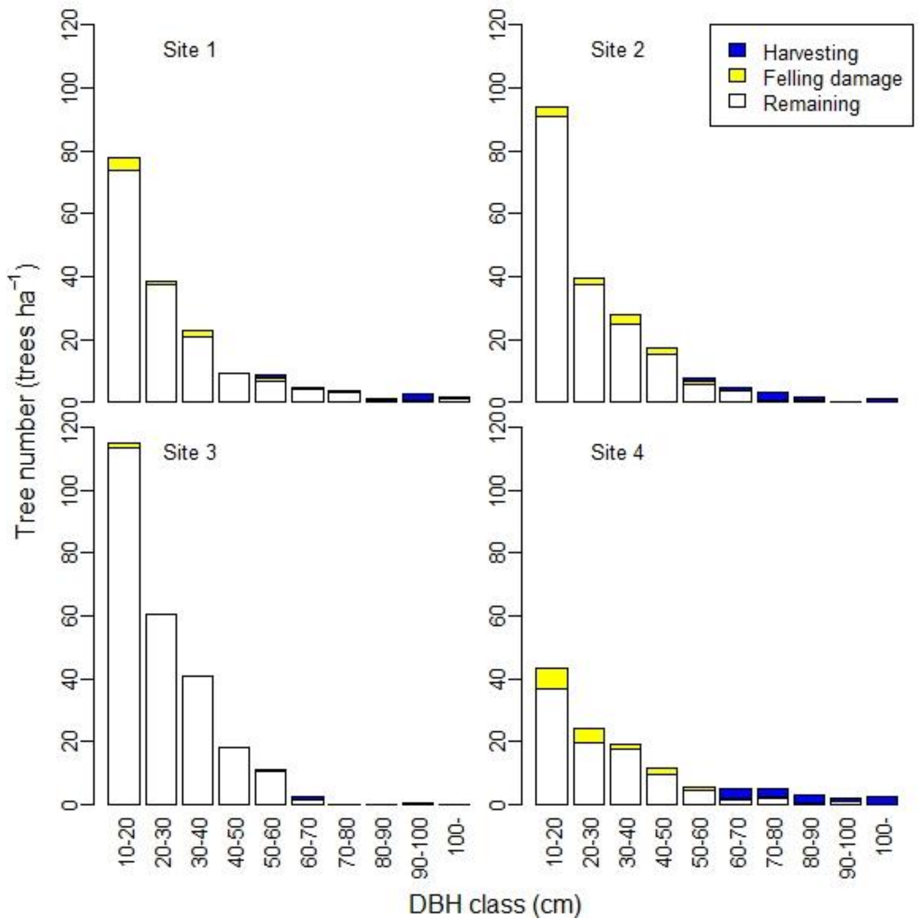


Figure 3.3. DBH distribution before harvesting. Trees at four sites are classified into harvested, damaged, and remaining trees.

Table 3.3. Harvesting intensity in nine subplots for four study sites

Subplots No.	Tree number (trees ha^{-1})				Stem volume (m^3 ha^{-1})			
	Site1	Site2	Site3	Site4	Site1	Site2	Site3	Site4
1	1	2	1	4	2.5	8.6	3.3	58.6
2	7	2	1	14	45.1	13.0	13.7	128.2
3	3	4	1	6	11.3	17.0	3.5	105.4
A	8	10	3	7	35.5	69.2	9.0	46.5
5	3	6	0	12	11.8	27.7	0.0	143.7
B	2	3	0	16	15.4	15.5	0.0	107.0
7	5	3	3	5	25.9	22.0	12.8	80.1
8	8	2	1	18	40.1	16.6	20.0	112.3
9	7	6	3	10	35.3	38.0	6.9	103.7
Average	4.9	4.2	1.4	10.2	24.8	25.3	7.7	98.4
Minimum	1.0	2.0	0.0	4.0	2.5	8.6	0.0	46.5
Maximum	8.0	10.0	3.0	18.0	45.1	69.2	20.0	143.7

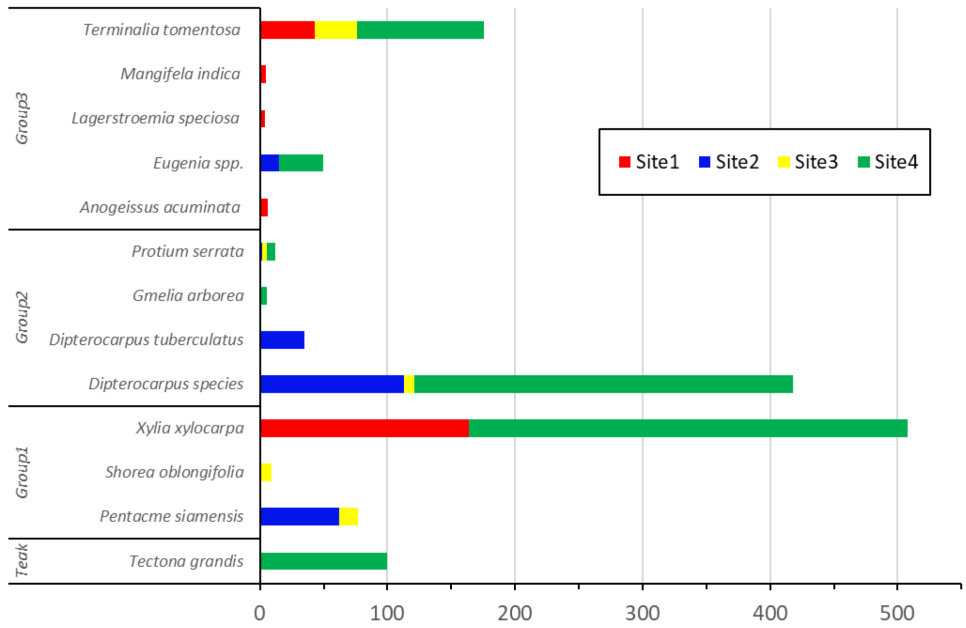


Figure 3.4. Stem volume (m3) of harvested tree species in 9-ha plot at each of four sites.

3.3.3. Felling damage

Among the eight subplots A and B, the rates of tree damage varied from 0 to 25.9% with an average of 6.7%. A similar variation was found for bamboo clump damage with an average of 6.8% (Table 3.2). Felling damage was found mainly for smaller trees ≤50 cm DBH (Figure 3.4). Felling damage to residual trees and bamboo clumps (%) in this MSS study was linearly related to harvesting intensity (trees ha-^{1}), and the regression lines were statistically identical between tree and bamboo damage (Figure 3.5 and Table 3.4, $p = 0.861$). These linear relations for MSS were at the lowest level of those reported in the other three studies (Figure 3.5). The relationship for MSS tree damage was significantly lower than those reported by (Sist et al., 1998) ($p = 0.03$) and (Sist et al., 2003a) ($p = 0.005$) but not significantly different from those reported by (Van der Hout ,1999) ($p = 0.181$).

Table 3.4. The result of the linear model for felling damage (%)

Variable	Estimate	SE	t-value	*P*
Intercept	-3.226	2.812	-1.147	0.256
Harvesting intensity (trees ha^{-1})	1.762	0.397	4.437	<0.0001
Site: This study (trees) (reference)				
Site: This study (bamboo)	0.698	3.976	0.176	0.861
Site: Sist *et al.* (1998)	7.575	3.409	2.222	0.030
Site: Sist *et al.* (2003)	12.920	4.440	2.910	0.005
Site: Van der Hout (1999)	7.941	5.871	1.353	0.181

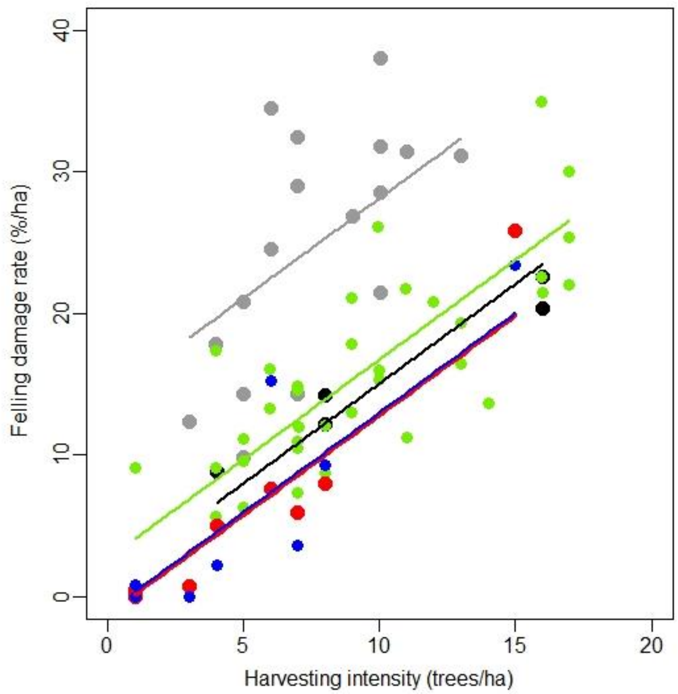


Figure 3.5. Relationships between harvesting intensity (trees ha-1) and felling damage (%) for residual trees (red) and bamboo clumps (blue) detected in this MSS study (n=8 each for tree and bamboo damage) compared with those reported by (Sist et al., 1998) (green), (Sist et al., 2003a) (gray), and (Van der Hout, 1999) (black).

3.3.4. Disturbance caused by elephant skidding

After felling operations, the officer in charge determined the cross-cutting points for each felled tree to obtain the best log lengths and to reduce wastage, and then branded respective hammers both on the stump and each log to confirm legality. Then, the logs were dragged away by elephant power from the felled tree stump to a temporarily constructed log landing, which was usually beside the forest road or at one end of the feeder. At Site 1, tree felling operations were conducted during late December. When we re-visited the site in March of the following year, we did not find disturbed soils from elephant skidding within the 9-ha plot. Indeed, the forest soil had become covered with forest debris and the dragging route or pathway of elephants was undetectable (Khai et al., 2016). At Sites 2, 3, and 4, we checked the ground disturbance in December, about 3-months after the tree felling operation was completed. At these three sites, we also did not detect disturbed soil from elephant skidding, which had been conducted about 3–4 months ago. The disturbance by elephant skidding was hard to detect when we checked only 3–4 months after the operations.

3.3.5. Ground disturbance by forest roads, log landings, and the other machine-disturbed area

Forest roads constructed using a bulldozer (D65-A6 type) at the four sites had similar widths with an average of 5.4 m at the berm level. The main difference among forest roads was the length; the shortest was 39.7 m ha^{-1} (Site 3) and the longest was 112 m ha^{-1} (Site 4). Multiplying the forest road width and length gave a total area directly under forest roads of 459, 403, 215 and 582 m^2 ha^{-1} at Sites 1–4, respectively (Figure 3.6). Another form of ground disturbance was the log landings constructed temporarily for collecting and measuring logs at each site (Figure 3.6). At Site 1, we did not find a log landing but we noticed that feeder roads had been constructed, and one end of four feeder roads was used as the log landing area. At Site 2, there were three log landings accounting for 687.8 m^2 9-ha^{-1} or 0.76% of the total area, while at Site 3, there were two log landings accounting for an area of 296.8 m^2 9-ha^{-1} or 0.33% of the area. At Site 4, we recorded a total of 14 log landings accounting for 2866 m^2 9-ha^{-1} or 3.18% of the total area. Apart from forest roads and log landings, we also observed additional ground disturbances in the form of extra machine maneuvering or machine disturbed areas (MDA) around the log landings or nearby the forest roads, especially at Sites 2 and 4 (Figure 3.6). At Site 2, there were three MDA accounting for 342 m^2 9-ha^{-1} or 0.38% of the total area. At Site 4, there were 11 MDA accounting for 2264 m^2 9-ha^{-1} or 2.52% of the total area.

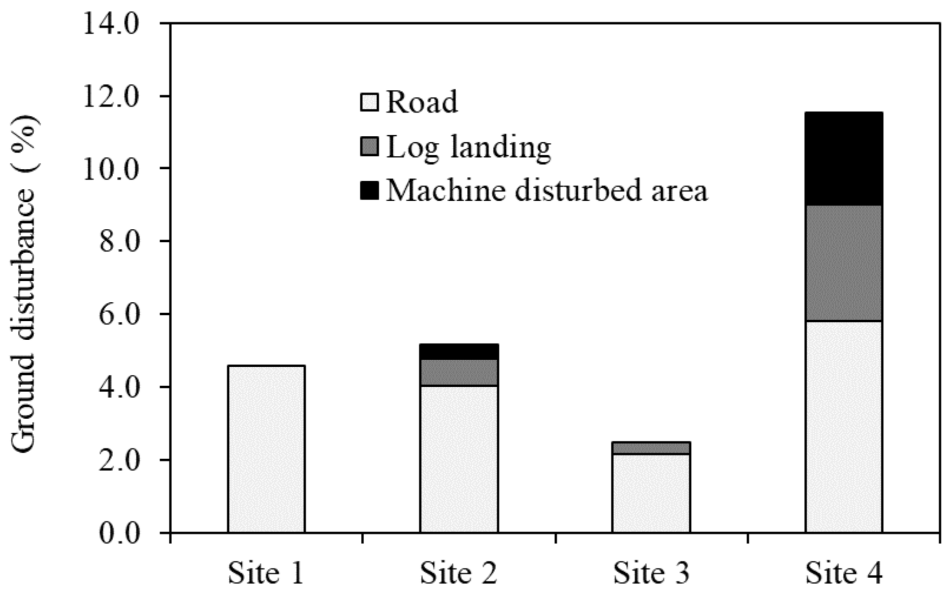


Figure 3.6. Ground disturbances; roads, log landings, and machine disturbed areas at the four study sites.

Overall, the total ground damage (forest road + log landings + machine disturbed area) recorded at Sites 1, 2, 3 and 4 accounted for 4.6%, 5.2%, 2.4% and 11.6% of the total area, respectively (Figure 3.6). The ground disturbance (%) of MSS was linearly related to harvesting intensity (trees ha-1) (n=4, Figure 7). This MSS relationship was significantly lower than that of the CON method ($p = 0.002$), but not different from that of the RIL method ($p = 0.235$) (Figure 3.7 and Table 3.5).

Table 3.5. The result of the linear model for ground disturbance (%).

Variable	Estimate	SE	t-value	*P*
Intercept	0.075	2.279	0.033	0.974
Harvesting intensity (trees ha^{-1})	1.141	0.316	3.611	0.002
Method: MSS (reference)				
Method: CON	6.811	1.921	3.546	0.002
Method: RIL	2.354	2.008	1.173	0.253

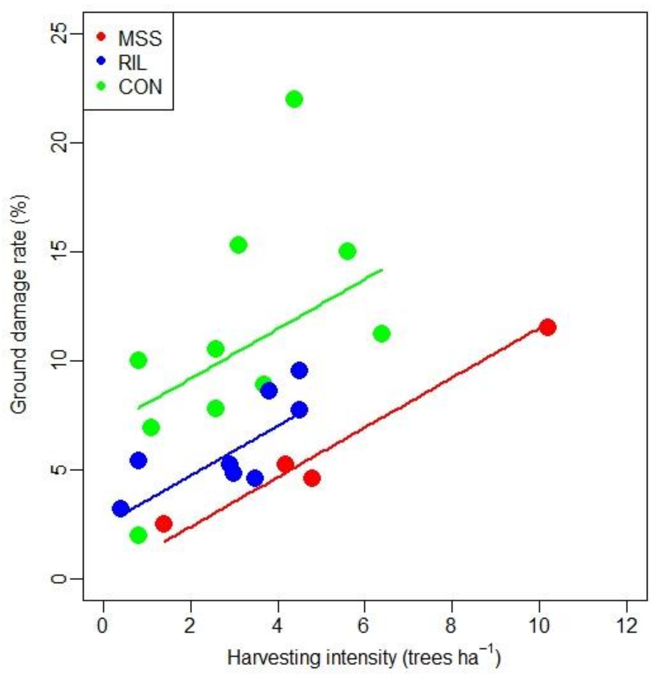


Figure 3.7. Relationship between harvesting intensity (trees ha^{-1}) and ground disturbance (%) caused by logging roads, skid tails, log landings, and other machine disturbed areas) detected in this MSS study (n=4), and calculated from RIL and CON data from six references.

3.4. Discussion

3.4.1. Harvesting intensity

Under the MSS, like in selective logging used in other tropical other counties, only a few large trees with ≥MDCL are harvested as commercial species. In a total of 36 1-ha subplots surveyed in this study, three species were dominantly harvested with a total average harvesting intensity of 5.2 trees ha-1 (39.9 m^3 ha^{-1}). This average value is similar to other values reported for Myanmar; 4.8 trees ha^{-1} (Lin, 2006) and 6.0 trees ha^{-1} (Ne Win et al., 2012) and is between the relatively low (3–4 trees ha^{-1}) and high (8–10 trees ha^{-1}) values reported for the Amazon and Southeast Asia, respectively (Sist et al., 2007). However, there were considerable variations among the 1-ha subplots, from 0 to 18 trees ha^{-1} (143.7 m^3 ha^{-1}). Such a wide variation in harvesting intensity has been found in meta-analyses of data from many countries (Picard et al., 2012; Pereira et al., 2002; Webb et al., 1997; Martin et al.,2015) and in case studies within a country (Sist et al., 1998; Sist et al., 2007) indicated that applying only the MDCL rules can lead to a high harvesting intensity, because it is simply determined by the density of harvestable timber trees. This was the case in our study, especially at Site 4 where there were many large dipterocarp trees (Figures 3.3 and 3.4). This finding confirms that the harvesting intensity of MSS is not necessarily low if only the MDCL rules are adopted.

3.4.2. Felling damage and effectiveness of directional felling towards bamboo

We were interested to compare the level of felling damage to residual trees observed in our study with those reported in other studies. Normally, tree damage caused by felling operations does not differ significantly between RIL and CON (Sist et al., 1998; Sist et al., 2003a). Rather, logging damage to residual trees is closely related to harvesting intensity, as determined in meta-analyses using data from many countries (Webb et al., 1997; Martin et al., 2015; Picard et al., 2012) and in case studies from single counties (Sist et al., 2007; Sist et al., 1998). Relationships with harvesting intensity were also confirmed in this study for both damage to residual trees and bamboo clumps (Figure 3.5). The relationship detected in this MSS study was at the lowest level compared with those reported in other studies (Figure 3.5). Interestingly, the linear relationship between felling damage and harvesting intensity was statistically identical for residual trees and bamboo clumps (Table 3.4 and Figure 3.5). This implies that the probability of felling damage is the same between residual trees and bamboo clumps and does not support that directional felling towards bamboo would be effective to reduce residual tree damage, as suggested by (Khai et al., 2016). (Sist et al., 1998) stated that techniques to significantly reduce felling damage to residual trees were not yet available in the tropics, since the felling damage intensity mainly depends on biophysical factors such as tree height, crown size, and topography. The MSS guidelines recommend to fell trees towards bamboo clumps rather than toward residual commercial trees. However, we observed that it is difficult to control the felling direction, and trees tend to be felled in the direction of the natural lean. Therefore, on the basis of our results, the best method to substantially decrease felling damage is to limit harvest intensity (Sist et al., 1998). We cannot indicate a specific limitation of the maximum harvesting intensity on the basis of our results, but (Sist et al., 1998) recommended a maximum of 8 trees ha-1 to reduce logging damage by 50% compared with that of CON. Other studies have quantitatively confirmed that larger felled trees cause more felling damage (Chheng et al., 2015). Thus, another way to reduce felling damage is to harvest smaller trees.

3.4.3. Ground disturbance and effectiveness of elephant skidding

In this study, the ground damage (%) of MSS had a linear relationship with harvesting intensity, and this relationship was at the lowest level as compared with those reported in studies on CON and RIL, but not significantly different between MSS and RIL. We suggest that the lowest level of ground disturbance in MSS may be because elephants are used for skidding in Myanmar, while machines are used in other countries. An elephant can drag logs through narrow spaces <1-m wide and the construction of paths is not necessary (Ne Win et al., 2012). In addition, existing footpaths and small lanes can be used as elephant skidding tracks (MoF, 2000). The soil disturbance was so slight that we did not detect ground disturbance by elephant skidding at 3–4 months after the logging operations. In contrast, machine skid trails are the most destructive factor causing tree mortality and ground disturbance in CON in other tropical regions (Sist et al., 1998; Bertault et al., 1997). For instance, the reported proportions of MDA from machine skidding were 6.8%–12.2% in Para, Brazil (Asner et al., 2004; Pereira et al., 2002), 4.2%–5.6 % in southern Amazonia (Feldpausch et al., 2005), 10.1% in the Paragomminas region, Brazil (John et al., 1996) and 2.3%–5.2% in southern Para, Brazil (Verissimo et al., 1995). Even at RIL sites, skid trails occupied 7% of the surface area in Eastern Amazon, Brazil (Sist et al., 2007) while, in Malaysia, they occupied 3.5% of the surface area (Pinard et al., 2000). Considering the extensive damage by skid trails in other tropical regions, this study confirms that the minimal logging damage resulting from elephant skidding operations is the main advancement of selective logging in Myanmar (Khai et al., 2016).

Our field survey confirmed that skidding by elephants has a clear limitation in terms of their physical power. The maximum log weight a single elephant can pull is restricted to 2 tons. An elephant can skid 300–600 m^3 timber per year using a harness and chains attached to the log (Lin et al., 2006), with a recommended maximum slope of 10%–15% for uphill skidding (MoF, 2000). When the harvesting intensity is higher in terms of both the tree size (DBH) and quantity on steeper terrain, more mechanical power is required for skidding operations, in addition to the construction of forest roads and log landings. Consequently, there is a greater disturbed area when bulldozers are used. Because of the large extent and numbers of log landings at Site 4, log landings and BDA occupied 3.2% and 2.6% of the total logged area, respectively. To reduce ground disturbance from machines, it is recommended to avoid harvesting large trees on steep slopes where elephants cannot work. In addition, retaining large trees in production forests would be beneficial as seed sources and for biodiversity conservation (Gustafsson et al., 2012).

3.5. Conclusions

Regarding the working hypotheses on MSS disturbance arising from a previous study at a single site, our results from 36 1-ha subplots covering four sites showed that:

1) Harvesting intensity based on the MDLC rules of the MSS is not necessarily low, and can even be high (i.e. >10 trees ha^{-1});

2) The relationship between harvesting intensity and felling damage for MSS was at the lowest level of those reported, but directional felling towards bamboos is not effective to reduce felling damage;

3) The relationship between harvesting intensity and ground disturbance for MSS was at the lowest level of those reported because elephants are used for skidding. However, elephant skidding is unsuitable for large trees and/or in areas on steep slopes.

To reduce MSS disturbance to residual trees and the ground and logging damage, we suggest to avoid harvesting large trees that cannot be dragged by elephants, because machines can cause additional ground disturbance. In addition, only following the rules of MDCL can lead to a high harvesting intensity of >10 trees ha^{-1}; thus, a limit to the maximum harvesting intensity is also recommended.

Chapter 4

Using a tree-based approach to evaluate logging damage in a tropical mixed deciduous forest of Myanmar: comparison with cases in Cambodia

4.1 Introduction

Selective logging in tropical forests plays an important role in meeting wood demand nationally and internationally. More than 400 million ha of natural tropical forests is now in permanent timber estates, and at least 20% of all tropical forests were logged from 2000 to 2005 (Edwards and Laurance, 2013). One of the most important parameters for evaluating the sustainability of selective logging of tropical forests is the damage to residual trees caused during felling and skidding. Numerous studies in the three major areas that contain tropical rainforests (Latin America, Central Africa, and Maritime Southeast Asia) have demonstrated that reduced impact logging, which consists of carefully planned and controlled felling and skidding by well-trained operators, can reduce the damage to the residual stand and soil by 50% under a moderate logging intensity (e.g. Sist and Ferreira, 2007).

Many studies have quantified the damage caused by selective logging in tropical rain forests, but very little is known about the damage to other forest types in the tropics. In addition, most of these studies adopted an area-based approach, in which descriptive statistics of the logging damage rate (%) within given areas that were subject to different logging intensities were provided. In contrast, few studies have used individual tree-based and statistical modeling-based approaches, which would enable one to estimate logging damage more stochastically. Recently, (Chheng et al., 2015) used a multinomial logistic model to predict the probability of felled trees causing severe, slight, or the residual and felled trees and the usefulness of the tree-based approach to increase the accuracy and comparability of logging damage estimates from different sites.

Myanmar is a timber-producing country on the Southeast Asian mainland, and it has tropical seasonal forests that receive less precipitation and experience lower temperatures than tropical rainforests. In Myanmar, a forest management system known as the MSS has been practiced in natural forests since 1856. Under the MSS, teak and a few commercially important hardwood species are selectively harvested based on a few principle rules such as a 30-year felling cycle, a MDCL and an AAC calculated using forest inventory data. The MSS has used elephants for most skidding operations, which are believed to have fewer impacts than heavy machines that are used commonly in other countries. With more than 100 years of experience with continuous timber extractions, the MSS can be considered to be a sustainable practice, and it is suitable for maintaining multispecies, natural teak-bearing forests (Dah., 2004). However, recent studies using remote sensing have revealed that forest degradation, defined as a reduction of canopy cover, has been occurring in selectively logged forests in Myanmar over the past several decades (Mon et al., 2010, 2012). One of the reasons for degradation in the production forest is a shorter felling cycle exceeding AAC for some compartments, and this deficient practice is carried out because Myanmar's forests have been facing high pressure from increased resource utilization associated with population growth and high demand from neighboring countries (Mon et al., 2012; Springate-Baginski., et al., 2014). These recent studies raise a question regarding the sustainability of the recent selective logging of Myanmar, but this has been addressed by very few studies. Therefore, as a step in evaluating the sustainability, we investigated the extent of logging damage to residual trees that was caused by recent harvesting operations.

In this study, to evaluate the logging damage caused by the recent selective logging of Myanmar, we used tree- and modeling-based approaches that were used by (Chheng et al., 2015) in Cambodia. Our main objective was to identify the similarities and differences in logging damage between forests in Myanmar and Cambodia, as well as other countries, whose stand structures are substantially different.

4.2 Materials and methods

4.2.1 Study site

This study was conducted in Bago Yoma, Myanmar, which has the longest history of implementing the MSS. The study site was located in compartment 29 (17°13′22″N, 96°22′54″E) in the South Zamaye reserved forest in the territory of Bago Township. Clayey and sandy soils are common. The topography of this compartment is generally mountainous with steep slopes, whereas the study sites of (Chheng et al., 2015) in Cambodia are nearly flat. Mixed deciduous forests are found mainly in compartment 29. There are relatively few commercially important species, such as *T. grandis, Xylia xylocarpa*, and *Hopea odorata*, while *Lagerstroemia speciosa*, *Anisoptera scaphula*, *Mangifera indica*, and other lesser used species are common.

4.2.2 Timber harvesting

Within the 13-year period from 1999 to 2011, three successive hardwood timber extractions were conducted in 1999, 2004, and 2011, and two successive teak extractions were conducted in 2000 and 2009 in compartment 29 by the government-operated MTE. These extractions were much more frequent than the 30year felling cycle that was adopted as a basic rule of the MSS. The latest harvesting was conducted during 2011 to 2013 for 1422 marked trees. At the last harvest, tree density was quite small mainly because of recent harvesting under short interval. The exploitable tree size for harvesting is based on the species. For large tree species, such as *Dipterocarpaceae species, H. odorata, A. scaphula,* and *Parashorea stellata*, the minimum exploitable size is 78 cm DBH. The harvestable size for *X. xylocarpa, L. speciosa*, and *Lagerstroemia tomentosa* is 68 cm DBH, while that of other hardwood species is 58 cm DBH.

4.2.3 Field survey

A tree damage assessment was conducted on March 25 and 26 in 2012 after all operations by the plots were assessed using a method proposed by (Johns et al., 1996). In this method, tree damage to crowns, boles, and roots was ranked on a scale from minor to moderate to severe. Crown damage was ranked as severe if more than 66% of the crown was lost, moderate if 33–66% of the crown was lost, and minor if less than 33% of the crown was lost. Similarly, bole damage was ranked as severe when the bole was smashed, uprooted, or broken. Bole damage was ranked as moderate if more than 100 cm^2 of bark was removed, and it was ranked as minor if less than 100 cm^2 of bark was removed. Root damage was ranked as severe if more than 10% of the surface roots were damaged, and minor if less than 10% of the surface the MTE, such as felling, elephant skidding, and transporting, were finished in the research plots. Twenty stumps of recently logged trees were randomly selected. At each selected stump, a 0.1-ha (25 m × 40 m) sample plot was set along the felling direction so that each plot included only one stump and one crown of the single felled tree, following the method adopted by (Chheng et al., 2015). Within the sample plots, all trees with DBH ≥ 10 cm were enumerated. The damage classes of each tree in roots were damaged.

Our measurements were conducted after felling and skidding, and so, we cannot distinguish felling damage and skidding damage perfectly. As explained in (Chheng et al., 2015) in detail, however, most of residual tree damage found within the 0.1-ha plot surrounding the single felled tree was caused by felling rather than by skidding, because damage within the plot was mostly found in/near the remaining crown of felled trees on the ground, whereas skidding of only the bole is usually conducted toward the direction opposite to the remaining felled crown and the area disturbed by such skidding is relatively small within the plot. Therefore, discussion of this study focused on felling damage rather than skidding damage as in (Chheng et al., 2015).

4.2.4 Data analysis at the 0.1-ha scale

Following the method of (Chheng et al., 2015), the damage classes for each tree were reclassified into three categories: severe, slight, and no damage. Severe damage included severe damage to either the crown, bole, or roots, and slight damage included moderate or minor damage to either the crown, bole, or roots.

To evaluate the effects of the sizes of the residual and felled trees on felling damage, we used a multinomial generalized linear mixed model (GLMM) with the "olmm" function from the "vcrpart" package (Buergin., 2015) in the R environment for statistical computing (R Core Team., 2014). Three damage categories (severe, slight, and no damage) were used as the response variables. We chose no damage category as the reference against which severe and slight damage categories were compared, respectively. Thus, the multinomial GLMM with logit link functions gave two equations for slight or severe damage probability relative to no damage probability as the dependent variable. The fixed effects were the log-transformed DBH of the residual and felled trees, and the plot was considered to be a random effect. Data from 175 sample trees that were located in the twenty 0.1-ha plots were used to fit the model.

4.3 Results

4.3.1 Stand structure, felled trees, and felling damage

A large variation in stand structure was found among the 0.1-ha plots (Table 4.1). Before felling, the tree density ranged from 20 to 240 trees ha^{-1}, with a mean of 98 trees ha^{-1}, while the basal are ranged from 4.8 to 28.7 m^2 ha^{-1}, with a mean of 17.6 m^2 ha^{-1}. The DBH of the felled trees ranged from 66.6 to 171.2 cm, with a mean of 98.0 cm. The stem basal area for the single felled trees ranged from 0.35 to 2.3 m^2 $tree^{-1}$, with a mean of 0.84 m^2 $tree^{-1}$. Figure 4.1(a) shows the DBH distribution for the pooled data of all 175 residual trees after felling, and it shows fewer trees in lower DBH classes, compared with an Inverse-J shape that is typically found in tropical forests.

Table 4.1. Stand structure before and after felling, size of felled trees, and percentage of damaged trees for the twenty 0.1-ha sample plots.

	Mean	SD	Min.	1st qu	Median	3rd qu	Max.
Before felling							
Number of trees (trees ha^{-1})	97.5	52.4	20.0	70.0	85.0	122.5	240.0
Mean DBH (cm)	42.2	9.79	28.0	32.9	42.0	50.7	58.4
BA (m^2 ha^{-1})	17.6	6.8	4.8	13.4	17.9	22.5	28.7
After felling							
Number of trees (trees ha^{-1})	87.5	52.4	10.0	60.0	75.0	112.5	230.0
Mean DBH (cm)	33.6	9.37	19.4	26.1	30.5	39.8	50.7
BA (m^2 ha^{-1})	9.2	5.2	0.5	5.6	8.5	13.3	19.0
Felled trees							
DBH (cm)	98.9	30.8	66.6	74.2	90.3	118.8	171.2
BA (m^2 $tree^{-1}$)	0.84	0.55	0.35	0.43	0.64	1.11	2.30
Percentage of damaged trees*							
Severe damage (% 0.1-ha^{-1})							
Bole	8.36	0.15	0.00	0.00	0.00	11.98	64.30
Crown	4.81	0.08	0.00	0.00	0.00	9.60	25.00
Whole	13.16	0.19	0.00	0.00	10.10	14.90	78.60
Slight damage (% 0.1-ha^{-1})							
Bole	2.38	0.05	0.00	0.00	0.00	1.08	16.70
Crown	2.12	0.06	0.00	0.00	0.00	0.00	25.00
Whole	4.50	0.07	0.00	0.00	0.00	7.40	25.00
Total damage (% 0.1-ha-1)							
Bole	10.73	0.19	0.00	0.00	0.00	12.95	71.40
Crown	6.93	0.19	0.00	0.00	2.15	11.90	25.00
Whole	17.66	0.21	0.00	0.00	13.65	20.55	85.70
No damage (% 0.1-ha^{-1})	82.34	0.21	14.30	79.45	86.35	100.00	100.00

*There was no root damage

The percentages of damaged residual trees also varied among the 20 plots (Table 4.1), while there was no damage to roots for all the plots. The total damage rate, including severe and slight damage, ranged from 0.0% to 85.7%, with a mean of 17.7%. The severe damage rate for the whole tree (bole + crown) (13.2%) was larger than the slight damage rate (4.5%). Figure 4.1(b) shows the proportion of damage levels for each DBH class using pooled data from the 175 residual trees. Severe damage was highest in the smallest DBH class, and less and no severe damage were found in the 20–50 cm and more than 50 cm DBH classes, respectively. In contrast, the slight damage percentage was relatively constant in DBH classes less than 50 cm. Neither severe damage nor slight damage was found for residual trees larger than 50 cm DBH. The no damage percentage was lowest for the smallest DBH class, and it reached 100% for trees with greater than 50 cm DBH.

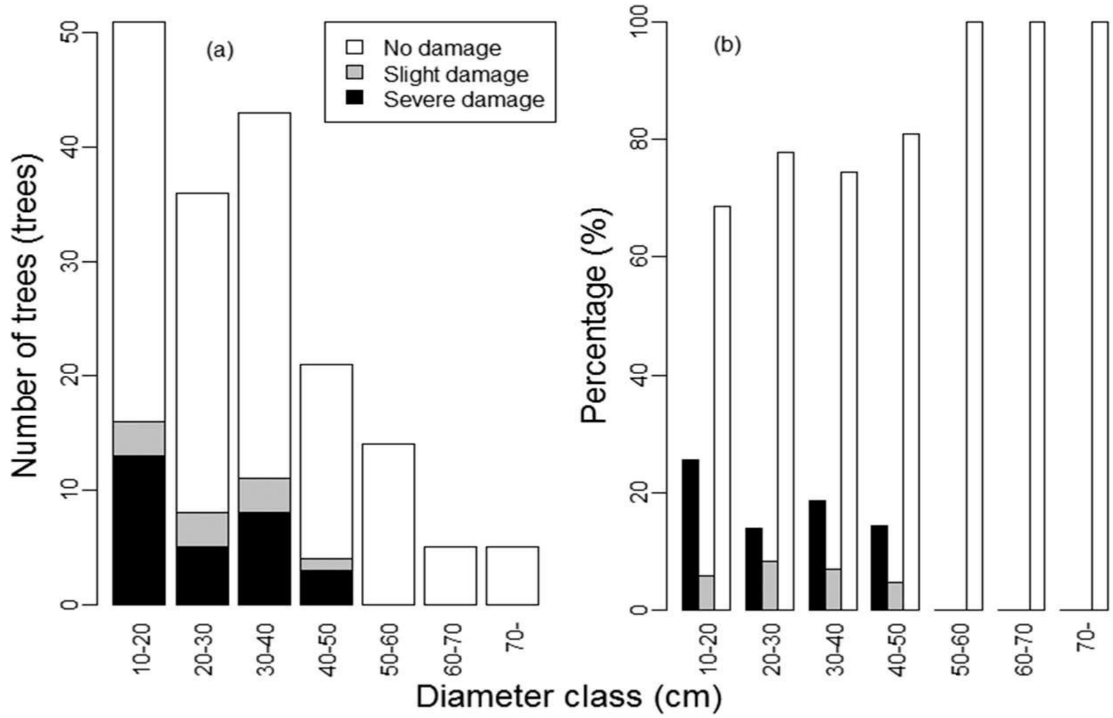


Figure 4.1. Number of residual trees with different damage levels (a) and the damage proportion within each DBH class, using pooled data of all 175 residual trees from the twenty 0.1-ha plots.

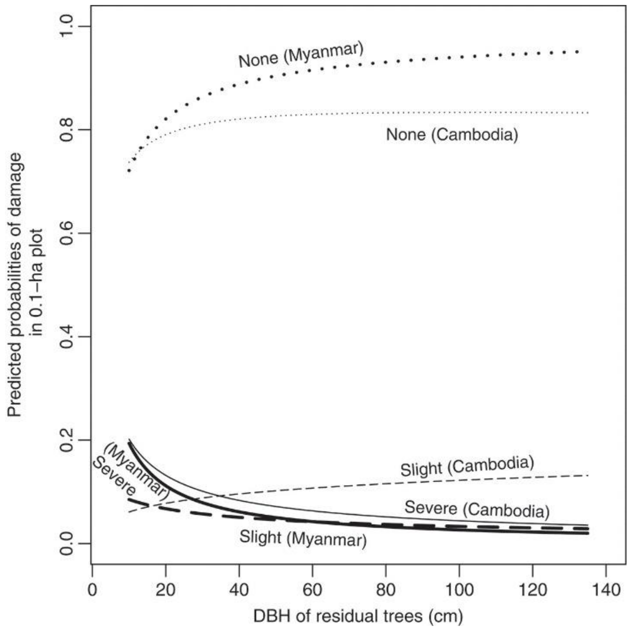
4.3.2 Probability of damage to residual trees caused by felling one tree per 0.1-ha plot

An analysis of the multinomial GLMM showed that the inclusion of the log-transformed DBH of only the felled trees (Akaike information criterion [AIC] = 214.3, chi squared p = 0.0177) or both the felled and residual trees (AIC = 214.2, chi-squared p = 0.016) into the fixed effects was statistically significant compared with a constant-only model (AIC = 218.3). However, the model using only the DBH of the residual trees as the fixed effect was not significantly improved (AIC = 217.4, chi-squared p = 0.0838). Table 4.2 shows the estimates of two equations from multinomial GLMM using slight or severe damage probability relative to no damage probability as the dependent variable and the log-transformed DBH of the felled and residual trees as the predictors. The coefficient signs in Table 4.2 indicate that the probability of severe damage, compared with no damage, increased with increasing size of the felled trees, while it decreased with increasing size of the residual trees. Figure 4.2 shows the model prediction, and it indicates how the DBH of the residual trees relates to the probability of a residual tree sustaining severe, slight, or no damage when the DBH of the felled tree was 90.3 cm, the median of the 20 felled trees. Figure 4.2 includes the curves that were predicted using the model that was developed by (Chheng et al., 2015) in Cambodia when the DBH of the felled trees was 90.3 cm. It can be seen in Figure 4.2 that there are relatively similar trajectories between the severe damage probabilities in Myanmar and Cambodia, but not for the slight damage and no damage probabilities. The slight damage probability in Myanmar was almost constant over the residual tree DBH (Figure 4.2), while it increased significantly in Cambodia, thereby reflecting the differences in the probability of no damage.

Table 4.2. The results of two equations from the multinomial generalized linear mixed model using slight or severe damage probability relative to no damage probability as the dependent variable.

Damage category	Variable	Estimate	SE	z Value	p	Odds ratio
Slight damage	Intercept	–5.268	17.029	–0.309	0.7571	
	Log of DBH of residual trees (cm)	–0.444	1.434	–0.310	0.7569	0.642
	Log of DBH of felled trees (cm)	0.865	2.999	0.288	0.7731	2.375
Severe damage	Intercept	–12.061	5.445	–2.215	0.0267	
	Log of DBH of residual trees (cm)	–0.954	0.739	–1.290	0.1969	0.385
	Log of DBH of felled trees (cm)	2.882	1.216	2.371	0.0177	17.853

Figure 4.3 shows the effects of the DBH of the felled trees on the predicted probability of a residual tree sustaining severe, slight, or no damage when the DBH of residual trees was 30.5 cm, the median of the means of the 20 plots. It also includes the model prediction by (Chheng et al., 2015) in Cambodia when the residual tree DBH was 30.5 cm. The forests in Myanmar and Cambodia showed similar trends of an increasing probability of severe damage, a constant probability of slight damage, and a decreasing probability of no damage with increasing DBH of the felled trees (Figure 4.3). The clear differences between the two cases are illustrated in the slopes of the trajectories for the severe and no damage probabilities, while these cases exhibited similar probabilities of slight damage, which were almost constant over the felled tree DBH.



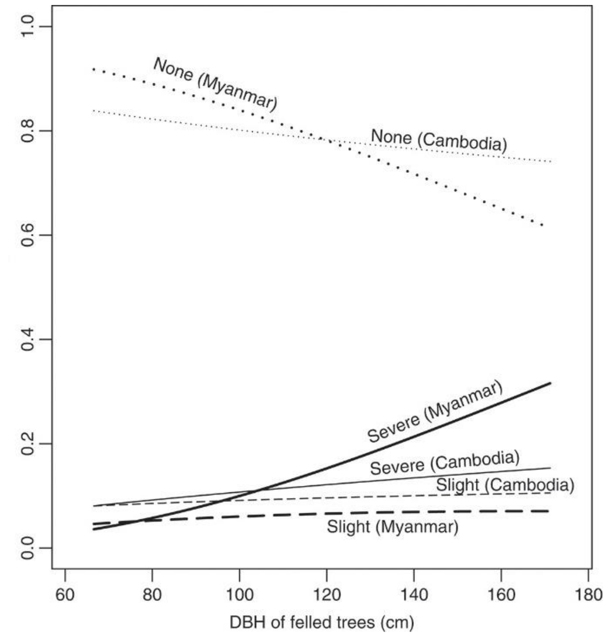


Figure 4.2. Effects of DBH of the residual trees on the predicted probability of a residual tree exhibiting severe, minor, or no damage. The thicker and thinner lines of each damage level represent the predictions from this study in Myanmar and from the model developed by (Chheng et al., 2015), respectively. For this example of the model prediction, the medium DBH (90.3 cm) among the 20 felled trees in this study was used.

Figure 4.3. Effects of DBH of the felled trees on the predicted probability of a residual tree exhibiting severe, slight, or no damage. The thicker and thinner lines of each damage level represent the predictions from this study in Myanmar and from the model developed by (Chheng et al., 2015), respectively. For this example of the model prediction, the median DBH (30.3 cm) of the residual trees in the 20 plots in this study was used.

4.4 Discussion

There have been many studies of the damage to residual trees caused by selective logging in the tropics, especially in tropical rain forests. Studies have shown that there are many factors that affect felling damage, such as the sizes of felled and residual trees (Picard et al., 2012; Chheng et al., 2015), stand density, the abundance of lianas that connect tree crowns, crown dimensions, and terrain (Medjibe et al., 2011). One of the objectives of our study was to examine whether the size dependency of felling damage that has been found in tropical evergreen and semi-evergreen forests in previous studies could also be found in our study site of a tropical mixed deciduous forest in Myanmar. The exceptional characteristic of our study site is that the stand density of residual trees with DBH ≥ 10 cm is very low, only 98 trees ha^{-1} on average. This is much lower than commonly reported values, which range from 400 to 500 ha^{-1} in tropical rain forests (Kao et al., 2010), 345 trees ha^{-1} (Chheng et al., 2015) in a tropical seasonal semi-evergreen forest in Cambodia, and those reported in tropical mixed deciduous forests in Myanmar (297 trees ha^{-1} in Yedashe (Lin., 2006), 168–312 trees ha^{-1} in Oak Twin (Oo and Lee., 2007), and 604–975 trees ha^{-1} in Popa Mountain Park (Zaw Htun et al., 2011)). As mentioned above, the very low stand density resulted from the highly frequent cutting cycles, which consisted of three and two harvests for hardwood and teak, respectively, within the last 13 years, although a 30-year rotation has been a rule of the MSS.

One of the unique observations of this study is that there was neither severe nor slight damage of the residual trees with DBH ≥ 50 cm. In contrast, previous studies reported high rates of severe and/or slight damage for large trees (Bertault and Sist., 1997; Webb., 1997; Chheng et al., 2015). The exceptional sparseness of the standing trees at our study site may be responsible for the lack of damage to large trees. In addition, large dominant trees tend to be scattered, not concentrated. Under this condition, it could be easier for operators to control the felling direction to avoid damaging large trees. In order to quantify the effect of tree density on the probability of logging damage, we tried to include standing residual-tree density as a fixed effect together with DBH of the felled and residual trees in the multinomial GLMM, but the inclusion of tree density did not significantly improve the constant-only model (chi-squared $p = 0.0625$). One of reasons for this insignificance of tree density in GLMM may be that our 20 sample plots are biased to lower tree density with the mean of 98 trees ha^{-1} in the range from 20 to 240 trees ha^{-1} (Table 4.1). Therefore, more data from plots with wider range of tree density will be needed for the further analysis. Contrary to the sample plots from our study, plots with higher tree density can be obtained from compartments following the MSS rule of a 30-year felling cycle (Khai et al., 2016).

In our study, we followed the field sampling method and data analysis of the multinomial model that was used by (Chheng et al., 2015) in a tropical semi-evergreen seasonal forest in Cambodia, which made it possible to directly compare the two cases. A similarity of the model predictions in the two cases was found in the trajectories of the relationship between the severe damage probability and residual tree size. In both cases, the probability of severe damage was highest (around 0.2) in the lowest DBH class, and it decreased with increasing residual tree DBH. Such size dependency of severe damage was also found in other studies (Bertault and Sist., 1997; Webb., 1997; Alder and Silva., 2000). However, there were clear differences between the two cases. Specifically, there was an increasing trend of the probability of slight damage with residual tree size in Cambodia, whereas it had an almost constant relationship up to a tree size of 50 cm DBH in Myanmar. Other studies showed that slight damage increased until tree size reached approximately 30– 50 cm DBH, and then, it decreased (Bertault and Sist, 1997; Webb, 1997; Alder and Silva, 2000). The relatively large variability in the trends of the slight damage probability among these studies may indicate that slight damage is affected by various factors that differ among the study sites, while the probability of severe damage to small residual trees is similar for different sites. In the case of our study, relatively small sample size (10 trees) of slight damage may also be an obstacle to find a clear trend of slight damage.

Other similarities between the sites in Myanmar and Cambodia were found in the dependency and independency of severe damage and slight damage, respectively, on felled tree size. A dependency on felled tree size was also found for total damage (severe + slight) in other studies (Jackson et al., 2002; Medjibe et al., 2011). However, as shown in Figure 4.3, the slope of the curve relating severe damage to the size of the felled trees was steeper in Myanmar than in Cambodia. The underlying reason is not clear, but large differences in topography may be a possible cause, as the Myanmar site is very steep, while the study sites in Cambodia are nearly flat. Steeper slopes may cause more severe damage to residual and felled trees of the same size. Further research is needed to confirm this assumption about the effects of topography on felling damage, as quantitative data that address this issue are not available.

The average total damage rate caused by one felled tree was 17.7% in the 0.1-ha plot (Table 1). Thus, the total damage rate in the 1.0-ha unit can be estimated to be 1.77% when the felling intensity is 1 tree ha^{-1}, based on the assumption that the number of residual trees in a 1.0-ha unit can be linearly extrapolated from the number of tress in the 0.1-ha plot (Chheng et al., 2015). This damage rate ha^{-1} is within the range of estimates for a tropical rain forest in Guyana (van der Hout, 1999) (1.64%), a tropical rain forest in Indonesia (1.97%), and a tropical semi-evergreen forest in Cambodia (2.02%) (Sist et al., 1998; Chheng et al., 2015).

4.5 Conclusions

Using the same tree- and modeling-based approach, our study made it possible to directly compare the logging damage probability between cases in Myanmar and Cambodia, whose stand structures and topography largely differ. At both sites, the probability of severe damage was negatively and positively related to the sizes of residual and felled trees, respectively. In contrast, the sites differed in terms of the relationship between the probability of slight damage and the size of residual trees, as well as the sensitivity of the probability of severe damage to felled tree size, which could be caused by differences in stand density and terrain between the two sites. Once we obtain data regarding the range of stand density and terrain, the multinomial GLMM can easily test whether such factors are statistically significant as fixed effects. Additional field surveys using the same tree-based approach could answer the hypotheses that arose from this study.

Chapter 5

Stand structure, composition and illegal logging in selectively logged production forests of Myanmar: Comparison of two compartments subject to different cutting frequency

5.1. Introduction

Selective logging is a common practice for timber production in tropical natural forests. There have been increasing global concerns about sustainability of tropical selective logging in terms of timber production (Kammesheidt et al., 2001; Sist and Ferreira, 2007), biodiversity conservation (Edwards et al., 2012; Putz et al., 2012; Burivalova et al., ;2014, Edwards et al., 2014), and carbon and/or energy exchange (Miller et al., 2011; Zimmerman and Kormos, 2012; Sasaki et al., 2012; Medjibe et al., 2013; Griscom et al., 2014; Pearson et al., 2014). The determination of appropriate cutting cycle or frequency and AAC is crucial to ensure the sustainability of tropical selective logging (Kammesheidt et al., 2001). Many growth and yield models have already been developed and widely used for improving cutting cycles to ensure sustainable yield and stand structure (Kammesheidt et al., 2001; Sist et al., 2003b; Van Gardingen et al., 2006). It is doubtless that such models are necessary to predict the future of forest stands under different management options. There have also been numerous studies using field surveys to examine effects of selective logging on stand structure and species composition (e.g. Brown and Gurevitch, 2004; Putz et al., 2012; Gourlet-Fleury et al., 2013; Burivalova et al., 2014; Edwards et al., 2014b). However, such field studies mostly evaluated short- or long term effects of a one-time logging operation (Panfil and Gullison, 1998; Kammesheidt, 1998; Parrotta et al., 2002; Okuda et al., 2003; Villela et al., 2006; Kao and Iida, 2006; Rutten et al., 2015), and so there are still limited field data showing the results of repeated logging under different cutting cycles.

Myanmar has a long history (since 1856) of the forest management system known as the MSS. The dominant forest type under MSS is tropical mixed deciduous forest, with teak and a few commercially important hardwood species selectively harvested. The principle rules of MSS are a cutting cycle of 30 years, MDCL for each commercial species, and AAC calculated from forest inventory data. MSS has been using elephants for most skidding operations, which is considered to have less impact than the heavy machines commonly used in other countries. With more than one hundred years of experience in continuous timber extraction, the MSS can be considered a sustainable practice and suitable for maintaining multi-species, natural teak-bearing forests (Dah, 2004). However, studies using remote sensing have revealed that forest degradation, defined as a reduction of canopy cover, has been increasing in selectively logged forests in Myanmar during recent decades (Mon et al., 2010, 2012). In efforts to fulfill the ever-increasing short-term demand of wood, timber extraction in some compartments has been done with shorter intervals than the standard cutting cycle of 30 years or with over-harvesting beyond the prescribed AAC. Such deficient practices could be some of the reasons for degradation of production forests in Myanmar (Mon et al., 2012). Another reason may be illegal logging in those forests (Mon et al., 2012). However, there has been very limited field evidence to verify how stand structure and species composition are degraded, and which species and tree size are illegally cut after repeated logging operations.

The objective of this study was to show field evidence of forest degradation in a selectively logged production forest of Myanmar. We compared stand structure, commercial species composition, and incidence of illegal logging between two stands subject to different cutting frequencies during a recent 18 years. A specific point of the study was to evaluate stumps for quantifying the amount and pattern of illegal cutting, as distinct from legal cutting.

5.2. Methods

5.2.1. Study site

The study sites are located in Bago Yoma, which has the longest history of MSS. We selected two compartments 93 (17°50'48"N, 96°7'19"E) and 29 (17°13'22"N, 96°22'54"E) in the South Zamaye Reserved Forest (RF) within Bago Township (Fig. 5.1). This RF has 119 compartments with total area 79,613 ha. The areas of compartments 93 and 29 are 740 ha and 1238 ha, respectively (Fig. 5.1). Our criteria to select two compartments 93 and 29 to be compared were that (1) the cutting frequencies were largely different, (2) the locations were relatively close within the same RF and (3) the timings of the latest legal logging operations were close in recent years. Here, there is a typical tropical monsoon climate with two distinct seasons, a wet period from the end of May through October and dry period from November through May. Mean annual rainfall is 3360 mm (Bago City) with average humidity 82.9%, and mean annual temperature is 26.7 °C in the Bago District.

Timber extraction with shorter cutting cycles than the 30-year MSS standard has been done in many compartments of South Zamaye RF in recent decades, separately for teak and other hardwood species. In compartment 93, timber harvesting during 2012 was the first instance of hardwood extraction after 1995. In compartment 29, there were two teak extractions in 2000 and 2009 and three other hardwood extractions in 1999, 2004 and 2011. Although there was no documentation available for timber extraction prior to 1995 in either compartment, old stumps indicated that timber was harvested at least twice before that year. In this study, we refer to compartments 93 and 29 with low and high cutting frequencies as LCF and HCF sites, respectively.

5.2.2. Logging operations

Under MSS, tree species are classified into six commercial species groups; teak, and Groups I–V. Teak is the most valuable, and its commercial value as timber decreases from Group I through V. *Xylia xylocarpa, Pentacme siamensis* and *Dalbergia oliveri* are the representative species of Group I, and Group V has lesser-used species (LUS). Exploitable tree size for harvesting varies with species. For potentially large tree species such as *Tectona grandis*, Dipterocarpus spp., *Hopea odorata*, *Anisoptera scaphula* and *Parashorea stellata*, the minimum exploitable DBH is 78 cm. The DBH for *Xylia xylocarpa*, *Lagerstroemia speciosa* and *Lagerstroemia tomentosa* is prescribed at 68 cm, whereas other hardwood species are set at 58 cm. Staff of the Myanmar Forest Department select and mark trees to be cut. Then, felling and skidding operations are carried out by the government-side Myanmar Timber Enterprise and/or its subcontracting agent, normally July through December. It is a rule that trees are to be felled toward bamboo clumps rather than toward residual trees, to avoid unnecessary tree damage. Skidding of logs away from felled tree stumps to a log deck where the logs are temporarily collected is done with elephant power. Forest roads for log transportation are usually constructed at the end of the rainy season, generally after November when the soil hardens. Two types of forest roads, forest access and feeder, are principally constructed at logging sites. These roads are usable only in the dry season.

In the latest operations, 1071 and 1422 trees were marked in compartments 93 and 29 in 2012 and 2011, respectively.

5.2.3. Field measurements and data analysis

5.2.3.1. Compartment 93 or low cutting-frequency site (LCF)

At LCF prior to the latest felling in late December 2012, two 1-ha rectangular plots were established between 25 November and 10 December 2012, in an area with trees marked for felling. The base point of one 1-ha plot was selected to include marked trees, and the base line and cross lines were laid out in the northern and western directions from that point. The starting point of the other 1-ha plot was 100 m east of the base point. In determining the base point of the plots, we attempted to find a location representative as a production stand at which the plots included some of the trees marked for harvesting, while avoiding inaccessible areas, which are mainly too steep and/or lack of commercial species. In the two plots, DBH for all trees with DBH ≥ 10 cm and the number of bamboo clumps were measured prior to felling. For each bamboo clump, the number of culms and maximum and minimum culm DBH (cm) were measured for calculating basal area (BA, m^2) of each clump, as

$$BA_i = n \times D_{max} \times D_{min} \times {}^{\pi}/_{40,000} \text{ ,}$$

where BA_i is BA of the *i*th bamboo clump, *n* is the number of culms, and D_{max} and D_{min} are the maximum and minimum culm DBH in the *i*th clump, respectively (Thein et al., 2007). Species of trees and bamboo were identified with the aid of local foresters and field staff working in the extraction agency, and then confirmed by the checklist of (Kress and Lace, 2003). In December 2014, 2 years after felling operations, we visited the plots again to check whether the measured trees were illegally cut in the two 1-ha plots and to record tree number.

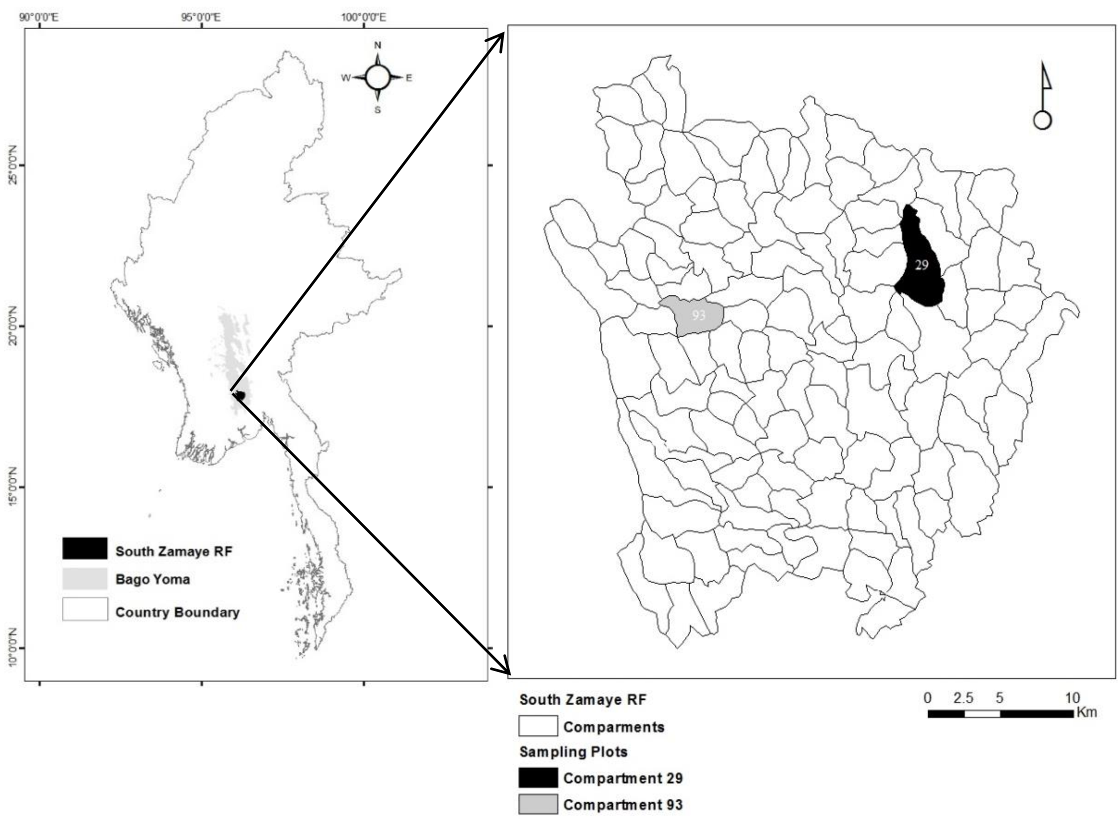


Figure 5.1. Location of the study sites in Compartment 93 with low cutting frequency (LUF) and Compartment 29 with high cutting frequency (HCF), South Zamaye Reserved Forest, Bago Yoma, Myanmar.

5.2.3.2 Compartment 29 or high cutting-frequency site (HCF)

Unlike at LCF, we did not measure stand structure prior to felling at HCF. Rather, we measured standing trees and stumps after the latest logging operation, from which we reconstructed stand structure prior to felling. In March 2012, two years after the last logging operation, we established a 1-ha rectangular plot in a logged area of HCF. In choosing plot location, priority was given to the inclusion of recently officially harvested stumps, to avoid inaccessible areas as a production stand. Those areas are mainly too steep and/or lack commercial species. It was easy to distinguish legally cut stumps from illegal ones, because the former were hammer-marked. In addition, the diameter of stumps from legal cutting was greater than the MDCL and stump height was ~0.4 m, whereas illegally cut stumps were smaller and higher. We measured the DBH of standing trees with DBH $\geq$ 10 cm and the largest and smallest culms within single clumps. We measured stump diameter (d) and height (h), from which we estimated stump DBH using the stem shape model (Thein et al., 2007): $DBH = d/(1.028h^{-0.114})$.

5.3. Result

5.3.1. Stand structure and species composition prior to most recent logging

Stand structure prior to the most recent logging, which was done in 2012 at LCF and 2011 at HCF, was substantially different between the two sites (Table 5.1). At HCF, tree density was only 41 ha^{-1}, about one-fifth the 176 ha^{-1} of LCF. BA (8.26 m^2 ha^{-1}) and species richness (15 species ha^{-1}) at HCF were also very low, nearly half the figures at LCF. The number of bamboo clumps at HCF (116 ha^{-1}) was also less than half that at LCF (260 ha^{-1}) but, because of a larger number of culms per clump (17.5 for HCF and 10.8 for LCF), BA of the clumps (8.17 m^2 ha^{-1}) at HCF was similar to that at LCF (8.25 m^2 ha^{-1}) and to tree BA at HCF (10.83 m^2 ha^{-1}). There were three bamboo species; *Bambusa polymorpha* was the dominant bamboo species and only a few clumps of *Cephalostachyum pergracile* at both LCF and HCF, while *Gigantochloa nigrociliata* was found as the second only at LCF.

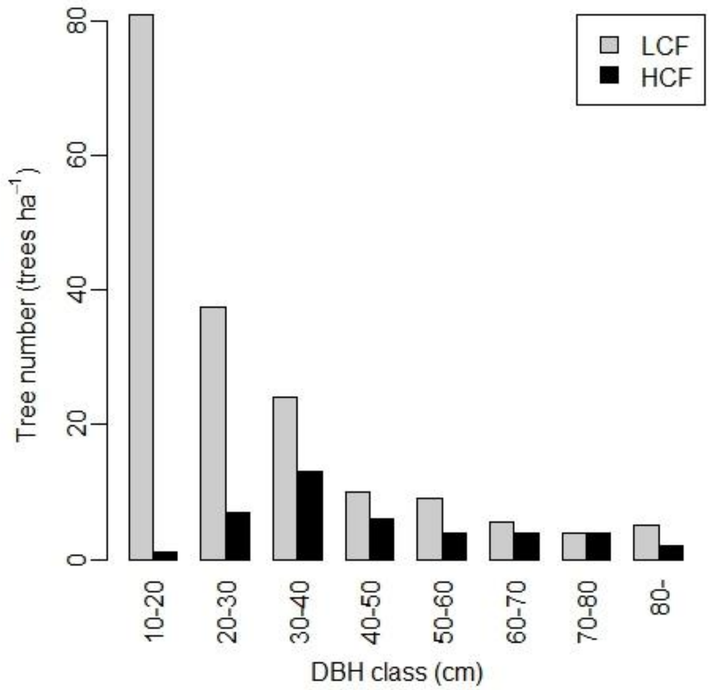


Figure 5.2. DBH distribution for low cutting frequency (LCF) and high cutting frequency (HCF) sites. The DBH distribution was also substantially different between LCF and HCF (Fig. 3.2; chi-squared = 37, $p < 0.0001$). An inverse -J shape of the distribution was found at LCF, but HCF had a shape with a single peak. Tree number was similar between the two sites for DBH classes > 60 cm, but their deviation increased in smaller DBH classes. There were only a few trees in the two smallest DBH classes at HCF.

Table 5.2 shows tree number of each commercial species group. Teak and all the other groups (I through V) had a substantial extent at LCF. In particular, *Tectona grandis*, *Xylia xylocarpa* (group I), *Terminalia tomentosa* (group III), *Anogeissus acuminata* (Group III), and *Homalium Tomentosum* (group V) are representative of mixed deciduous forests in this region. However, at HCF, there were low tree densities, and *Tectona grandis* and *Terminalia tomentosa*, the two main characteristic species in the area, were lacking. The DBH distribution of each species group is shown in Fig. 5.3. At LCF, all species groups except IV had DBH distributions resembling the reverse -J shape; tree numbers were largest in the smallest DBH class and they decreased with increasing DBH class.

Table 5.1 Stand structure before and after most recent logging, and legally and illegally cut trees for low cutting frequency (LCF) and high cutting frequency (HCF)

Attributes	LCF	HCF
Stand structure prior to the latest operations		
Tree density (trees ha^{-1})	176.0	41.0
Tree DBH (mean ± SD, cm)	30.6 ± 19.7	46.6 ± 20.1
Tree BA (m^2 ha^{-1})	16.4	8.25
Tree specise richness (counts ha^{-1})	34.5	15.0
Bamboo clump density (clumps ha^{-1})	260.0	116.0
Bamboo clump BA (m^2 ha^{-1})	10.8	8.17
Mean culm number per clump	10.8	17.5
Legal cut trees		
Cut-tree number (trees ha^{-1})	5.0	3.0
Cut-tree DBH (mean ± SD, cm)	91.6 ± 18.6	82.0 ± 12.8
Cut-tree BA (m^2 ha-1)	2.91	1.37
Cut-tree species number (counts ha^{-1})	2.5	3.0
Illegal cut trees		
Cut-tree number (trees ha^{-1})	6.0	18.0
Cut-tree DBH (mean ± SD, cm)	40.0 ± 21.8	39.9 ± 13.3
Cut-tree BA (m^2 ha^{-1})	1.92	2.48
Cut-tree species number (counts ha^{-1})	2.5	6.0
Stand structure of residual stand		
Tree density (trees ha^{-1})	165.0	20.0
Tree DBH (mean ± SD, cm)	26.5 ± 16.4	27.5 ± 22.2
Tree BA (m^2 ha^{-1})	12.5	4.39
Tree specise richness (counts ha^{-1})	34.5	11.0

LCF values are means for two 1-ha plots

Table 4.2 Tree density (ha-1) for each species group before and after cutting for low cutting frequency (LCF) and high cutting frequency (HCF)

Species group	Prior to most recent cutting		Legally cut trees		Illegally cut trees		Remainig Stand	
	LCF	HCF	LCF	HCF	LCF	HCF	LCF	HCF
Teak	22.5	0.0	0.0	0.0	3.5	0.0	19.0	0.0
Group I	17.5	2.0	2.5	1.0	1.0	1.0	14.0	0.0
Group II	11.0	24.0	0.0	1.0	0.5	14.0	10.5	9.0
Group III	31.0	2.0	2.0	1.0	0.0	0.0	29.0	1.0
Group IV	12.5	1.0	0.0	0.0	0.0	0.0	12.5	1.0
Group V	81.5	12.0	0.5	0.0	1.0	3.0	80.0	9.0
Total	176.0	41.0	5.0	3.0	6.0	18.0	165.0	20.0

LCF values are means for two 1-ha plots

5.3.2. Legally and illegally cut trees, and residual stands structure and composition

Tables 5.1 and 5.2 include information on legally and illegally cut trees. For legal cutting, respective felling intensities were 5 and 3 trees ha^{-1} at LCF and HCF, and average DBH was > 80 cm (Table 1, Fig. 4). On average, 3 species ha^{-1} were legally cut from various species classes (Table 2). For illegal cutting, almost half the remaining trees (18/38) at HCF were cut illegally among six species, mainly from the species group II (Table 5.2, Fig.5.4). At HCF, the illegally cut average DBH (39.9 cm) was much smaller than legally cut (Fig. 4), whereas illegally cut BA (2.48 m^2 ha^{-1}) was much larger than legally cut (Table 5.1). At LCF, 6 trees ha^{-1} were illegally cut (Table 5.1). Within the 2-ha area measured at LCF, we found that seven teak and two *Xylia xylocarpa* of Group I were cut illegally and sawn for timber near their stumps, and their average DBH was 50.4 cm. The other three smaller trees from Groups II and V were also cut but used for the saw pit, with average DBH = 22.2 cm. At HCF, however, we did not find such signs of sawing timber in and near the plot. Instead, we found charcoal kilns near the plot.

The remaining stand after legal and illegal cutting at HCF was greatly degraded just one year after legal cutting; tree density and BA were only 20 ha^{-1} and 4.39 m^2 ha^{-1}, respectively. Tree species number also declined, from 15 to 11 (Table 5.1). At LCF, changes two years after legal cutting were relatively small. The reduction in tree density was 6.3% (176 to 165 ha^{-1}) and only one species disappeared in the 2-ha area. Nevertheless, the reduction of tree BA was substantial, at 20% (16.4 to 12.5 m^2 ha^{-1}), 40% of which was attributed to illegal cutting (Table 5.1).

5.4 Discussion

5.4.1. Forest degradation

The annual deforestation rate of Myanmar, 0.95%, is one of the highest for a tropical country, but a much higher rate of 6.2%, has been reported for forest degradation, defined as a reduction of closed forest with canopy cover > 40% (FAO., 2010). Such a high degradation rate relative to deforestation has also been observed in the production forests of Bago Yoma (Mon et al., 2010). Overharvesting beyond AAC with short cutting cycles and illegal timber extraction could be causes of forest degradation in Myanmar production forests (Mon et al., 2012b), but there has been a dearth of field evidence verifying conditions of those forests. We found a strongly degraded condition with very low stocking (41 trees ha^{-1}, BA = 8.25, and 8.17 m^2 ha^{-1} for trees and bamboo) and less commercially important timber species without teak in the stand subject to HCF (a total of four times, or two times for each teak and other hardwood during logging over 17 years). This cutting frequency is much too high, well beyond the MSS standard 30-year cutting cycle. In contrast, stand structure (176 trees ha^{-1}, BA = 16.4, and 10.8 $m^2 ha^{-1}$ for trees and bamboo) was much better in the LCF stand, which had no logging records in the recent 17 years. A structure very similar to LCF is found in data from Kabaung RF, also in Bago Yoma (Thein et al., 2007). Study sites there were harvested in 2001 for the first time in 22 years, with 180 trees ha^{-1}, BA = 20.2, and 10.2 $m^2 ha^{-1}$ for trees and bamboo. LCF had a substantial extent of commercially important species in each DBH class (Fig. 5.3). For the example of teak, tree density was 22.5 ha^{-1}, there were at least two trees in each DBH class, and the number was larger in smaller DBH classes (Fig. 5.3). This figure concurs with the recommendation by (Sist et al., 2003c) that harvesting should be limited to species with density > one adult (> 50-cm DBH) tree ha^{-1}. These results call for renewed recognition of the importance of following the 30-year standard cutting cycle at a minimum. However, studies using simulation models or the stock recovery formula have suggested extending cutting cycles from 30 to 60 years, to ensure sustained yield in Venezuela (Kammesheidt et al., 2001) and Brazil (Kammesheidt et al., 2001; Van Gardingen et al., 2006), and from 35 to 40 years with reduced logging intensity in Indonesia (Sist et al., 2003b). Therefore, the MSS standard cycle should be reevaluated via such modeling approaches. Hence, tree growth measurements will be crucial, because there has been a dearth of growth data required for such modeling.

One of the greatest differences between LCF and HCF were found in DBH distribution, even prior to the most recent felling (Fig. 5.2). LCF showed the reverse-J shape, typical for a tropical natural forest, whereas HCF had very few trees with DBH < 30 cm and a modal distribution. As in other tropical countries, the MSS cuts only a few large trees more than the MDCL, for each commercial species (Fig. 4.4). Thus, it is common that felling and skidding operations of such large trees damage residual trees by as much as 20%, when felling intensity is 3–5 trees ha^{-1} (Picard et al., 2012). In addition, smaller residual trees are more subject to severe damage, resulting in higher mortality (Picard et al., 2012). Such felling and skidding damage may be one cause of the low number of small trees at the repeated logging stand. However, our study showed evidence that degradation is attributable to not only felling and skidding damage but also illegal logging, as mentioned below. In addition, the bamboo-dominated structure at HCF would hamper tree regeneration. It is reported that increased disturbance from tree cutting and charcoal burning has shifted dominance from various tree species to a few bamboo species (Larpkern et al., 2011). In the present study, the density of bamboo clumps (116 ha^{-1}) was much greater than that of trees (41 ha^{-1}). In such bamboo-dominated conditions, management of bamboos by controlling their distribution in areas of high bamboo density can be an important forest restoration method (Larpkern et al., 2011).

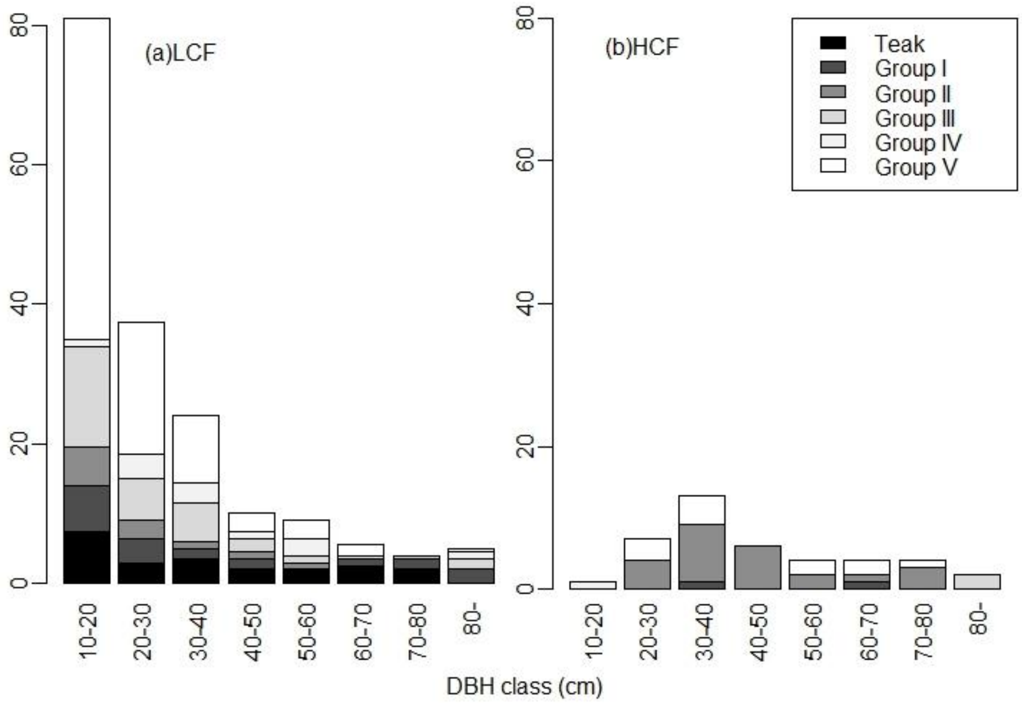


Figure 5.3. DBH distribution of each species group (teak and groups I–V) for low cutting frequency LCF (a) and high cutting frequency HCF (b) sites.

5.4.2. Illegal logging

Our field surveys revealed illegal logging one or two years after legal logging at both sites, but in different manners. At LCF, illegal logging focused on two species, teak and *Xylia xylocarpa*, which are the best and second-best commercially important species for sawn timber. At HFC, a large number trees were extracted, mostly from the middle size-classes, including various species for making charcoal. Such variable types of illegal logging should be considered in plans to combat illegal logging.

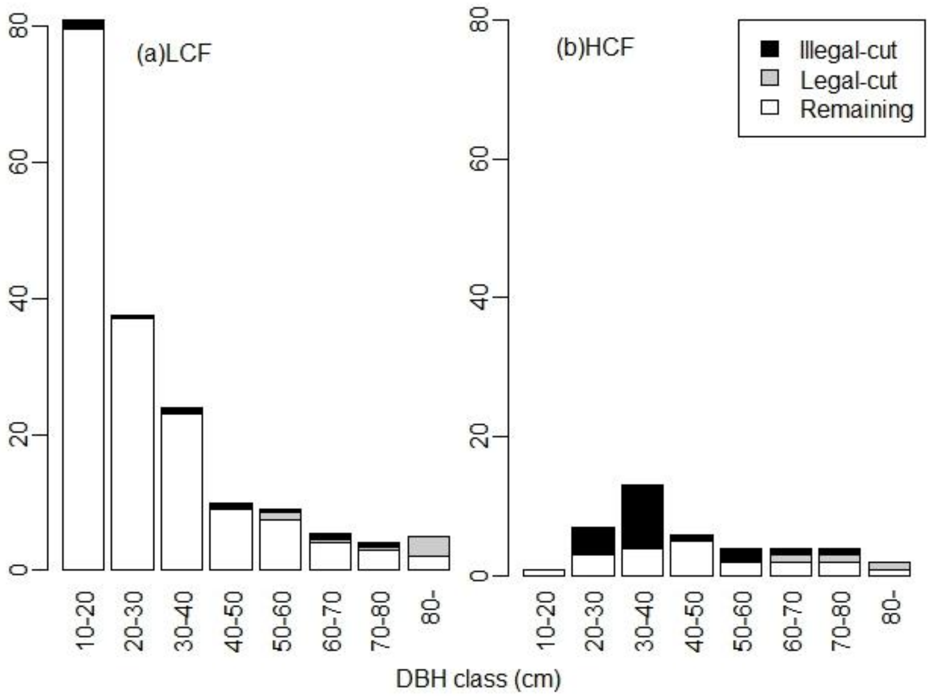


Figure 5.4. DBH distribution of legally cut, illegally cut and remaining trees for low cutting frequency LCF (a) and high cutting frequency HCF (b) sites.

Construction of logging road increases accessibility to logged sites, and so is considered a trigger of forest degradation and subsequent deforestation (Asner et al., 2006). In MSS, logging roads are constructed by bulldozer for use only in the dry season. Such temporary roads cannot normally be used after the subsequent rainy season, because of steep gullies and erosion in many parts. Old road tracks are commonly used for constructing new roads, so repeated operations over short intervals for road construction are likely to make a temporary road more physically stable. This would increase accessibility accordingly. In fact, we observed that the soil surface of temporary roads at HCF was relatively stable. Houses of bamboo were constructed along the logging roads at HCF but not at LCF. MSS has a regulation stating that logging roads should be destroyed after logging operations. Such attention to accessibility would be important to reduce illegal logging.

The illegal nature of timber harvests makes it difficult to locate and quantify overall amounts of timber harvested, largely because illegal logging frequently does not produce large canopy gaps visible on satellite images (Scabin et al., 2012). In our study, we were able to clearly distinguish illegal cutting from legal cutting based on hammer marks and size/height of stumps in the field. It can be time-consuming to estimate illegal logging from field surveys of stumps. However, recent forest inventories of many countries include stump measurements for carbon stock and biodiversity evaluation (Woodall et al., 2009). Thus, such stump measurements in regular forest inventories can be readily used for estimating the extent of illegal logging if there is a clear difference between legally and illegally cut stumps, as in the present study of MSS.

5.5. Conclusions

MSS, with its long history, is believed to be a form of sustainable forest management, with low-impact operation owing to elephant skidding and directional felling toward bamboos. However, the present study showed some evidence from field surveys that this belief is not justified when the MSS-standard cutting cycle of 30 years is not followed. We confirmed that repeated logging at shorter intervals can strongly degrade stands, with very poor stocking of even commercially lower-value species, especially with smaller tree size. The major reason for this was the repeated construction of logging roads, which increased accessibility and facilitated illegal cutting of even non-timber species for charcoal making. Conversely, the stand with less frequent cutting had a much better structure, with commercially high-value species for subsequent cutting-cycle operations. This confirmed the importance of following the MSS 30-year cutting cycle to ensure sustainability. More extensive and systematic surveys are needed to generalize our results of forest degradation related to cutting cycles in production forests of Myanmar and other countries. This would be possible if regular forest inventory programs include stump measurements for estimating not only carbon stock and biodiversity but also illegal cutting. This present study calls for an urgent rethink of logging operations with short cutting cycle and for rehabilitation of bamboo-dominated degraded forests where natural regeneration is difficult.

Chapter 6

Post-harvest stands dynamics over 5 years in selectively logged production forests in Bago, Myanmar

6.1. Introduction

Tropical forests, representing ~44% of global forests (1,770 million ha in area) (Keenan et al., 2015), represent a widely recognized important ecosystem for maintaining carbon stock and biodiversity, and they play key roles in the provision of nearly 15% of global timber (Blaser et al. 2011; Chheng et al., 2015). Consequently, attention has focused on the impacts of selective harvesting, which is a common operation in tropical timber production (Hari Poudyal et al., 2018) and the re-establishment of disturbed forests (Cole et al., 2014). Sustainable forest management for timber production demands that forest functions are maintained and that the growing stock recovers during the cutting cycle to allow the continuous provision of ecosystem services and sustainable yields of target species (de Avila et al., 2017). Thus, it is very important to obtain reliable information on stand dynamics and species compositional shifts after selective logging (Dionisio et al., 2018; Rozendaal et al., 2010).

In an attempt to assess the stand dynamics of disturbed tropical forests, comparative information on the changes in size structure, species composition and demographic processes, such as growth, mortality and recruitment, has been obtained (Amaral et al., 2019; Peart et al., 1998; Shima et al., 2018; Yamada et al., 2013; Yosi et al., 2011). These studies used data between two censuses at different periods or between disturbed and undisturbed control plots. Investigating the dynamics in post-harvest forests is not simple because forest structure is the result of natural processes, such as tree growth, mortality and recruitment, natural disturbances, such as forest fire and wind damage, and also human disturbances, such as illegal logging. However, only a few studies (Kao et al., 2010; Win et al., 2018b) have considered illegal logging, which may have considerably high effects on stand dynamics in tropical production forests.

Myanmar is a tropical timber-producing country in Southeast Asia that uses the traditional MSS, which evolved in the 1860s. The MSS originally focused on the sustainable production of teak, and the theories and practices have been subsequently applied to other commercial species (Forest Department, 2000). This system attempts to ensure sustained yields of commercial species using a 30-year cutting cycle, and the harvestable size is regulated using a

MDCL, which is 58 to 78 cm, depending on the species. The AAC is calculated based on the number of future harvestable trees that will reach the MDCL within the next 30 years, and an assumed diameter growth rate (0.32 cm $year^{-1}$) was adopted to predict the harvestable trees. Until recently, the forestry sector was responsible for approximately one-third of the country's total export earnings and was a major source of foreign exchange. Owing to its implementation for hundreds of years of selective logging in tropical production forests (Puettmann et al., 2015), the Myanmar selection system can be considered as a sustainable practice and suitable for maintaining multi-species, natural teak-bearing forests (Dah, 2004). However, studies using remote sensing have revealed that forest degradation, defined as the reduction of canopy cover, has occurred in selectively logged forests in Myanmar during recent decades (Mon et al., 2012, 2010). (Win et al.,2018a) used large-scale forest inventory data from the systematic sampling of 4 km × 4 km grids to reveal widespread forest degradation in the production forests of Myanmar, in which there were very few harvestable large trees of commercial species. In addition, (Win et al., 2018b) investigated legally and illegally cut stumps to reveal that the amount of illegally cut trees was much greater than legally cut trees and that illegal cutting increased after legal cutting. Under such negative forest conditions, the forest policy in 2016 eventually commenced a country-wide logging ban policy for 2016–17 and a 10-year fallow period in Bago Yoma, which is the main extraction area of Myanmar.

While the long-standing practices of Myanmar have been questioned since production forests were threatened by forest degradation, (Khai et al. 2016) reported that the Myanmar operations (felling, skidding and road construction) caused relatively limited residual trees damage and ground disturbance compared with tropical forest logging operations in other countries. In light of such research findings, illegal logging may be a main reason for forest degradation. However, the extent of illegal logging's impact on stand dynamics over time compared with the other components, such as natural mortality, and recruitment and growth of living trees, is unknown. Studies on the structures, growth rates and yields of natural teak forests in Myanmar started with the commencement of working-plan operations in as early as the late 19th century (Kyaw, 2003). The diameter growth rate (0.32 cm $year^{-1}$) of teak, based on tree ring counting at the time, was used for the AAC calculation. However, it is questionable whether the growth rates of production forests that have been subject to selective logging for one and a half centuries remain constant. Although data on growth rates of commercial plantation trees are common in Myanmar forestry, updated reliable data on the growth and yields of natural production forests are still lacking.

The objective of this study is to evaluate impacts of illegal logging on stand dynamics in a traditional production forest in Myanmar. For this, we investigate changes in growing stocks and species composition just before and for 5 years after official legal logging operations in two 1-ha established plots. Then, we compare the components of stand dynamics, including human disturbances (legal-cut, illegal-cut, collateral deaths from tree felling) and natural processes (mortality, recruitment and living tree growth).

6.2. Materials and methods

6.2.1. Study site

The study was conducted in Compartment 93 of South Zamaye Reserved Forests (RF) in Bago Yoma, a legendary forestry region in the lower central basin of Myanmar. The RF, composed of 119 compartments, is 79,613 ha in area, and the study site, Compartment 93, is 740 ha in area located at 17°50'48"N, 96°7'19"E (Figure 6.1). It has a typical tropical monsoon climate with two well-delineated seasons: a wet period from the end of May through October and a dry period from November through May. The mean annual rainfall is 3,360 mm, with an average humidity of 82.9%, and the mean annual temperature is 26.7 °C in Bago City (Forest Department, 2010), which is approximately 80 km southeast from the study site. The study site is not in an easily accessible area because it is situated upstream of the Zaungthu irrigation water reservoir in relatively undulating terrain. Tropical mixed deciduous forests, with the main characteristic species teak, *Xylia xylocarpa, Terminalia tomentosa* and *Bambusa polymorpha*, were mainly found at the site. Locally, the forest type is natural teak-bearing deciduous forest.

Timber harvesting during 2012–13 was the first instance of hardwood extraction from the study site since 1995. There were no accurate records available for timber extraction prior to 1995; however, existing old stumps indicated that timber was harvested at least twice prior to that year. Very old and decayed teak stumps were distinguishable by their texture, size > 73 cm, and low heights (~0.2 m), which met the criteria for felling teak (Khai et al., 2016). Other higher hardwood stumps of various sizes were believed to indicate trees extracted in the 1990s prior to the construction of the Zaungthu Dam adjacent to the study site.

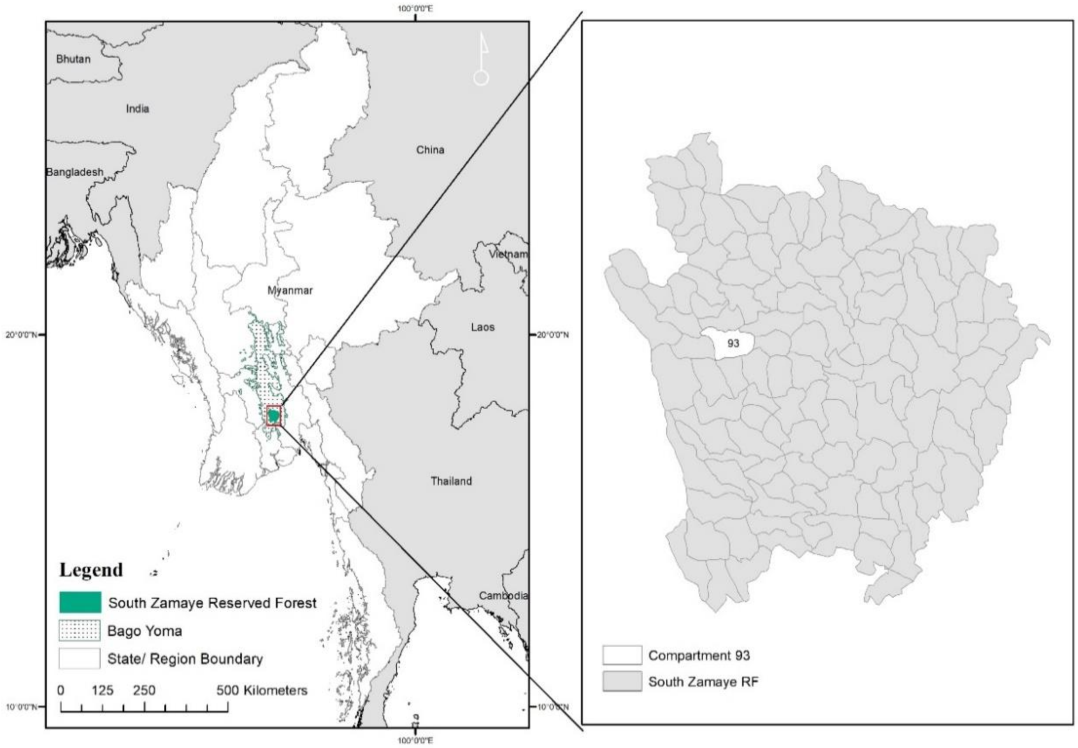


Figure 6.1. Location of the study site in Compartment 93, South Zamaye Reserved Forest, Bago Yoma, Myanmar.

6.2.2. Timber harvesting operation

For timber harvesting in Myanmar, tree species are classified into six commercial groups: teak and non-teak hardwoods into Groups I–V. Group I species are the commercially most important because the trees' economic value decreases from Group I to IV, and Group V contains the lesser-used species. Whether a tree can be legally harvested is determined by the prescribed MDCL, which varies with species and forest types in a geographical location. Timber harvesting plans for the extraction of T. grandis and non-teak hardwoods are usually determined separately. In the 2012–13 fiscal year, teak harvesting was not implemented in the study area. For hardwood species, the MDCL in the study site ranged from 58 to 78 cm, while for the major commercial species at the site, *X. xylocarpa, Lagerstroemia speciosa* and *T. tomentosa*, the MDCL was set at 68 cm (Forest Department, 2010). A total of 1,071 trees were marked by the Myanmar Forest Department to be extracted from Compartment 93 (Khai et al., 2016). The government agency, the MTE, performed the logging operations, which mainly included tree felling, log stumping and skidding, logging road construction and log transportation.

6.2.3. Field measeurments

A 9-ha rectangular plot (300 m × 300 m) with two inner 1-ha subplots, A and B (Figure 6.2), was established during December 2012. As a starting point for establishing the 9-ha plot, the south-east corner point of subplot A was subjectively located in an area with trees marked for felling, and the base and cross lines of each subplot were laid out in north–south and east–west directions, respectively, from that point (Khai et al., 2016). When we located the corner point of subplot A, we attempted to find a location representative of a production stand in which the plot included some of the trees marked for harvesting, while avoiding inaccessible areas that were too steep and/or lacked commercial species (Khai et al., 2016). Intensive tree measurements were taken in subplots A and B. All the standing trees with diameter at breast height (DBH) ≥ 10 cm were individually numbered and tagged prior to the tree felling operation, and each tree's species was identified. Immediately after tree felling, residual trees damaged by the felled trees were assessed (Khai et al., 2016). This investigation was completed in December 2012. In March 2013, when all the logging operations were completed, trees damaged as a result of the log skidding operation were traced and the number of trees removed owing to the road construction was determined. The area of the logging road was measured within the 9-ha plot.

In December 2017, 5 years after the felling operations, all the trees with a DBH ≥ 10 cm in subplots A and B were re-measured, newly recruited trees that reached 10 cm DBH were identified, and dead or missing trees were recorded.

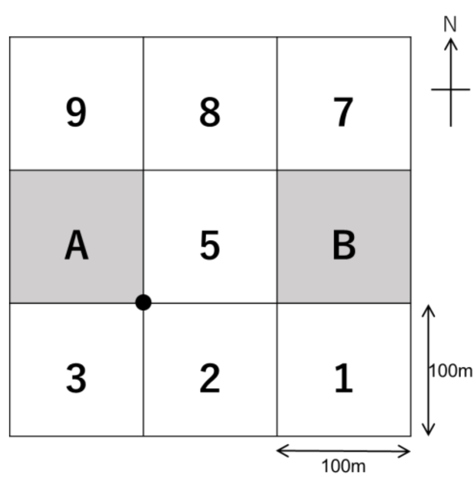


Figure 6.2. Layout of the nine 1-ha subplots in Compartment 93, South Zamaye Reserved Forest, Bago Yoma, Myanmar. The south-east corner of subplot A (black dot) was the starting point for establishing the plot.

6.2.4. Sampling of illegally cut trees

At the site, we were able to distinguish illegal cutting from legal cutting based on the official hammer marks, and the sizes and heights of stumps in the field. In Myanmar, the legality of harvested trees can be checked using the precise official hammer-marking of the Forest Department and the timber extraction agency, Myanmar Timber Enterprise. For timber harvesting, exploitable trees that have attained the prescribed MDCL, for example ≥ 58, 68 or 78 cm DBH, depending on the species at the site, are marked with two blazes, along with the selection felling (SF) number, at the lowest part of the bole height (below ~45 cm) and at just above or below the 1.3-m bole height. Immediately after the selected tree is felled, a series of hammer marks, such as SF number, number of marketable logs from the felled trees, the compartment code and the personal hammer of the officer in charge, are branded on the stump surface. Thus, stumps without branded hammer marks indicate illegally cut trees. In addition, illegal stumps are usually higher and smaller in size than the MDCL.

6.2.5. Data analysis

The stand-level attributes at pre-harvest (December 2012), 2-year post-harvest (December 2014) and 5-year post-harvest (Dec 2017) were examined for individual trees with a DBH ≥ 10 cm. The causes of changes over time were classified into human disturbances and natural occurrences. Human disturbances include (i) official logging operations (tree felling, tree skidding and road construction), including collateral tree death caused unintentionally during the official operations, and (ii) illegal cutting and collateral death caused unintentionally during tree felling. Natural occurrences include (iii) recruitment reaching a 10-cm DBH, (iv) natural deaths (mortality) of trees, both standing and fallen, and (v) growth of living trees. We placed trees that we could not located during the survey into the mortality category.

The annual mortality and recruitment rates were estimated using the following equation (Sist and Nguyen-Thé, 2002):

$$n_{1-2} = \frac{1}{t_{1-2}} \frac{n_2}{N_1} \times 100,$$

where n_{1-2} represents the rate of mortality or recruitment in a percentage of trees per year, t_{1-2} represents the time between measurements 1 and 2 in years, for mortality, n_2 represents the number of trees recorded during measurement 1 and dead at measurement 2 , while, for recruitment, n_2 represents the number of trees newly reaching a 10-cm DBH at measurement 2 and N_1 represents the number of trees in measurement 1 (Sist et al., 2002).

DBH increment of individual trees with DBH ≥10 cm were calculated for trees surviving at measurement times 1 and 2. Recruited trees and five outliers with unrealistic data, which may have resulted from measurement errors, were excluded from the increment analysis.

The volume of a standing tree was calculated using the following equation developed for trees having ≥ 20-cm DBH in Bago Yoma, Myanmar (Leech et al., 1986):

$$v = b0 + b1D + b2D^2 + b3D^3 \ldots\ldots bnD^n,$$

where v represents the tree volume over bark (m^3), D represents DBH (cm) and b_n values represent parameters estimated for each species or species group.

6.3. Results

6.3.1. Stand structure at pre-harvest

Prior to the tree felling operation in December 2012, the density of trees with DBHs ≥ 10 cm in the subplots A and B was 201 and 151 trees ha^{-1} (Table S1) with a basal area of 16.3 and 16.8 m^2 ha^{-1} (Table S2), and the volume of standing trees having ≥ 20 cm DBH was 111 and 131 m^3 ha^{-1}, respectively (Table 6.1). The DBH distribution among trees showed an inverted J shape, typical of tropical natural forests. The tree species richness was 45 and 41 species ha^{-1} in the subplots A and B respectively, and 58 species in a total of the 2-ha subplots. Among the 58 species, tropical mixed deciduous tree species of teak, *X. xylocarpa* (Group I), and *L. speciosa* (Group III), representing 12.8%, 9.38% and 9.38% of the tree density, respectively, were dominant. The species richness of bamboo was three in the 2-ha subplots, among which *B. polymorpha* was dominant with representing 74.8% of the total 519 bamboo-clumps.

Table 6.1 Changes in the volume (m³ ha-1) of trees with DBH ≥ 20 cm for all and each species group.

Years	All species			Species group (Mean of the subplots A and B)					
	Mean	Subplot		Teak	Group1	Group2	Group3	Group4	Group5
		A	B						
Stock in 2012 before legal operations	**121**	111	131	**25.6**	**22.7**	**4.1**	**18.0**	**19.9**	**30.7**
Legal disturbance in 2012	**-29.3**	-43.2	-15.4	**0.00**	**-15.6**	**0.00**	**-10.6**	**-0.76**	**-2.34**
Legal cut	-25.5	-35.6	-15.4	0.00	-14.9	0.0	-9.8	0.00	-0.81
Killed from legal-cut	-2.14	-4.28	0.00	0.00	-0.13	0.00	-0.25	-0.76	-0.99
Killed from road construction	-1.65	-3.31	0.00	0.00	-0.56	0.00	-0.56	0.00	-0.54
Stock in 2012 after legal operations	**91.7**	68.0	115	**25.6**	**7.16**	**4.10**	**7.33**	**19.1**	**28.4**
Illegal disturbance from 2012 to 2017	**-28.0**	-25.6	-30.5	**-21.2**	**-5.89**	**-0.40**	**0.00**	**-0.45**	**-0.09**
Illegal cut	-27.5	-24.6	-30.5	-21.2	-5.89	-0.40	0.00	0.00	0.00
Killed from illegal-cut	-0.54	-1.07	0.00	0.00	0.00	0.00	0.00	-0.45	-0.09
Natural changes from 2012 to 2017	**1.45**	2.58	0.33	**0.63**	**0.53**	**-0.38**	**0.29**	**-0.80**	**1.19**
Mortality	-7.94	-5.64	-10.23	-0.31	0.00	-0.90	-0.69	-2.73	-3.31
Recruitment*	-	-	-	-	-	-	-	-	-
Increment of living trees	9.39	8.23	10.55	0.94	0.53	0.52	0.98	1.93	4.50
Stock in 2017	**65.1**	45.0	85.1	**4.98**	**1.81**	**3.32**	**7.62**	**17.8**	**29.5**

* The volume of the recruited trees was not calculated because DBH of them was less than 20 cm.

6.3.2. Human disturbance

6.3.2.1. Disturbances caused by official logging operations

Within the subplots A and B (2 ha), 5.0 trees ha^{-1} of commercial hardwood trees (tree volume of 25.5 m3 ha^{-1}) were harvested from species groups I, III and V (Tables 6.1 and S1, Figure 6.3). The number of residual trees that were killed collaterally by the official harvesting operation was 5.5 trees ha^{-1} (Table S1). The size of officially harvested trees (mean DBH ± SD = 83.9 ± 20.5 cm) was relatively larger than the collaterally killed trees (Figure 6.3). The log skidding operation was conducted using elephants, but no trees were observed to be damaged as a result of skidding. The logging roads constructed for forest access and as feeders used 84 m ha^{-1} or 4.6% of the area. During the logging road construction, 8.5 trees ha^{-1} were cleared or destroyed, but the sizes of these trees were relatively small (Table S1 and Figure 6.3). As a result, the total tree loss during the official timber harvesting operation was 19 trees ha^{-1} (29.3 m^3 ha^{-1}), resulting in a reduction from 176 to 157 trees ha^{-1} (121 to 91.7 m^3 ha^{-1}) (Tables 6.1 and S1, and Figure 6.4).

6.3.2.2. Disturbances from illegal logging

We observed the trees that were illegally cut for 5 years after the official logging operations. The amount of illegal felling was 13.5 trees ha^{-1} (27.5 m^3 ha^{-1}) (Tables 1 and S1). Illegally cut trees were targeted to relatively large trees as well as smaller trees cut for use in saw pits (Figure 6.3). It should be also noted that only the most economically valuable species, *T. grandis* (teak) and *X. xylocarpa* (Group I), were mainly affected by illegal cutting (Figure 6.3). The numbers of trees that were collaterally killed as a result of felling illegally cut trees were 10.5 trees ha^{-1} (0.54 m^3 ha^{-1}), but the sizes of these killed trees were relatively small (Tables 6.1 and S1, and Figure 6.3). Overall, the numbers of illegally cut trees and the subsequent residual trees killed during felling amounted to 25.0 trees ha^{-1} (28.0 m^3 ha^{-1}) being lost over the 5-year post-harvest period (Tables 6.1 and S1).

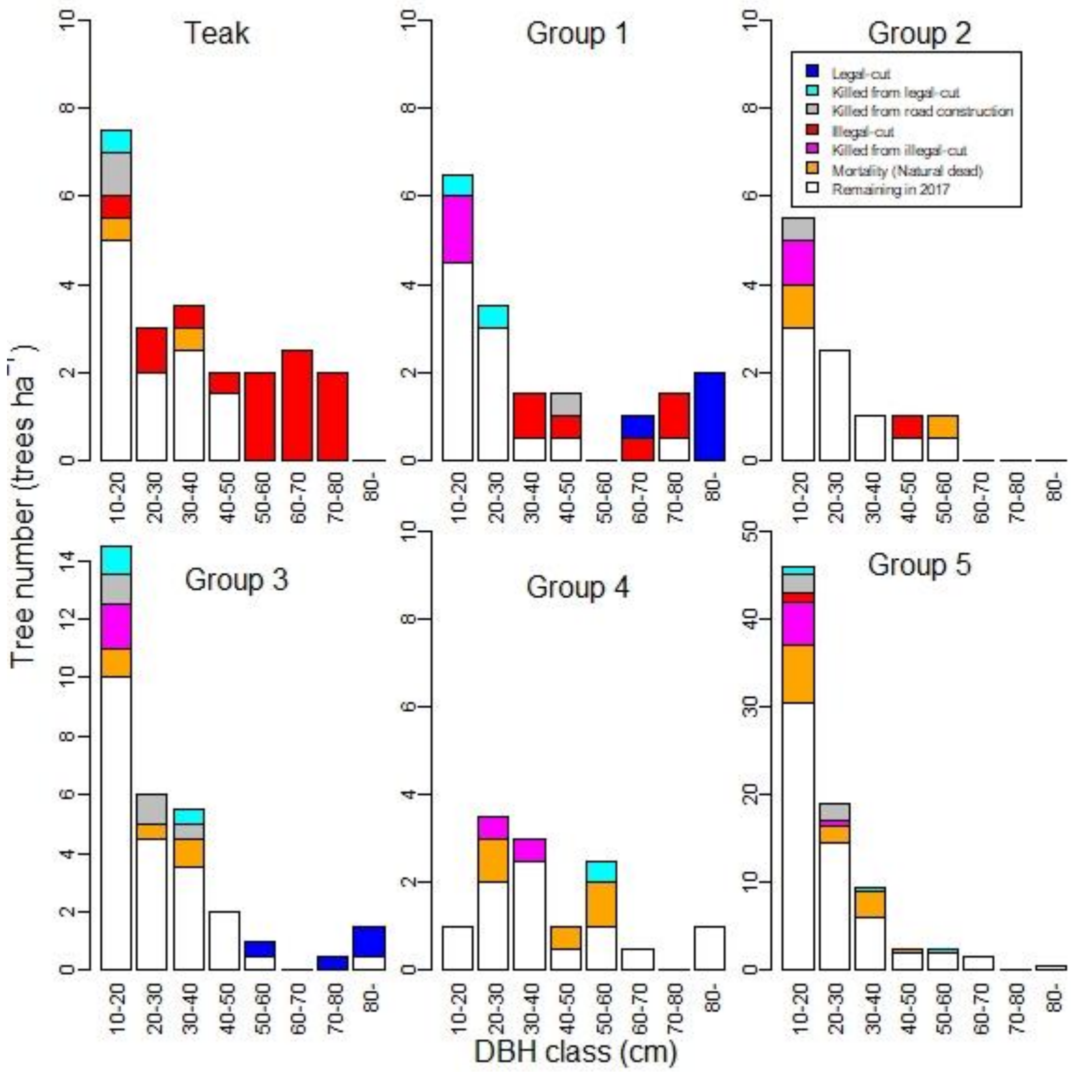


Figure 6.3. DBH distribution for each species group in Compartment 93, South Zamaye Reserved Forest, Bago Yoma, Myanmar in 2012 and their classifications in 2017.

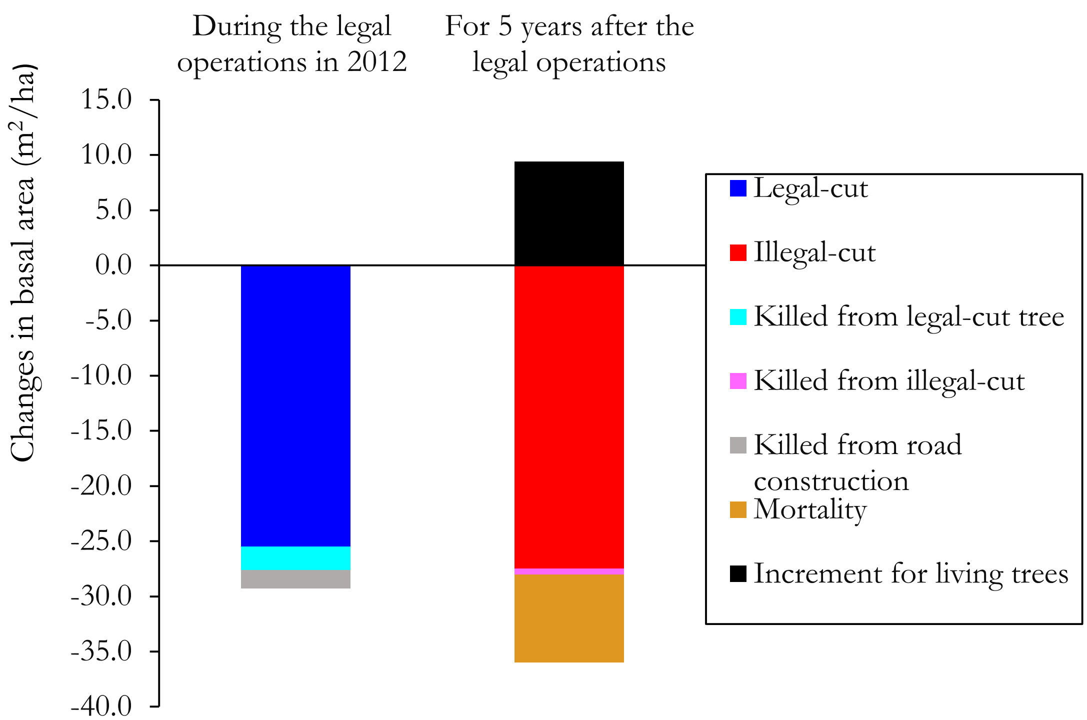


Figure 6.4. Changes in the volume (m^3 ha^{-1}) of trees with DBH ≥ 20 cm for each component of stand dynamics during the legal logging operations in 2012 and during the 5-year post-harvest period (2012–17) in Compartment 93, South Zamaye Reserved Forest, Bago Yoma, Myanmar

6.3.3. Natural occurrences

6.3.3.1. Mortality, recruitment and living tree growth

The mortality was 19.5 trees ha^{-1} (7.94 m^3 ha^{-1}) for the 5-year post-harvest period (Tables 6.1 and S1), and on an annual basis, the mortality rate was 2.5%. The mortality rate was greater for relatively smaller-sized trees and for species group 2-5 (Figure 6.3). The recruitment was 24.5 trees ha^{-1} for the 5-year post-harvest period (Tables 6.1 and S1), and the annual recruitment rate was 3.1%. For the recruited trees, DBH was relatively small between 10 to 20 cm, and thus, the basal area was relatively small (0.3 m^2) (Table S2) and the volume was not calculated since the volume equations are applicable only to trees with DBH ≥ 20 cm. Among species group, the recruitment was particularly small between 0 to 1.5 trees ha^{-1} for teak, *X. Xylocarpa* and Group 2 (Table S1).

The amount of the mortality and increment of living trees was relatively similar for all the trees (7.94 and 9.37 m^3 ha^{-1}) as well as for each species groups (Tables 6.1 and S2). As a result, the total change caused by natural occurrences, including mortality, recruitment and living tree growth, was relatively small for the 5-year post-harvest period (1.45 m^3 ha^{-1}). (Tables 1, S1 and S2).

6.3.3.2. Diameter growth rates

For all the species, the mean (± SD) of the annual DBH increment rate over the 5-year post-harvest period was 0.48± 0.30 cm $year^{-1}$, which is significantly larger than the standard growth rate of 0.32 cm $year^{-1}$ that has been traditionally used to calculate the sustained yield for the 30-year cutting cycle (t-test, $p < 0.05$). For each of the species group, the means for teak (0.54 cm), Group 1 (0.69 cm), Group 4 (0.55cm) and Group 5 (0.46) were significantly larger than 0.32 cm, but there was no significant difference for Group 2 (0.46 cm) and Group 3 (0.39 cm) (Table S3 and Figure S1).

6.3.3.3. Changes over the 5-year post-harvest period

There were substantial decreasing trends over the 5-year post-harvest period, with reductions of 46% (121 to 65.1 m^3 ha^{-1}) (Figure 6.5 and Table 6.1). Among species group, the large reductions from the legal operations in 2012 were found only for Group 1 and 3, while the large reduction after the legal operations occurred only for teak and Group 1 (Figure 6.5 and Table 6.1). Before the legal operations, teak and Group 1 shared 40% (48.3 m^3 ha^{-1}) of the total volume (121 m^3 ha^{-1}), but after 5-year post-harvest, the share decreased to be 10% while the other four species groups shared 90% (Figure 6.5 and Table 6.1).

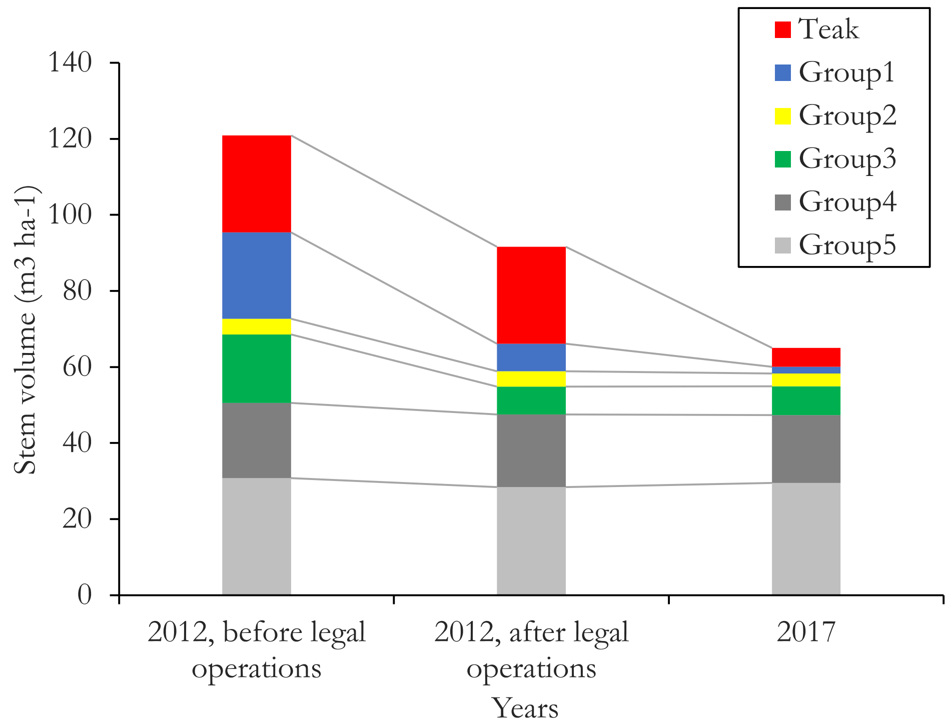


Figure 6.5. The volume of trees with DBH ≥ 20 cm for each species group before and after the legal operations in 2012 and in 2017 in Compartment 93, South Zamaye Reserved Forest, Bago Yoma, Myanmar.

6.4. Discussion

6.4.1. Human disturbances

Logging intensity is a critical factor that determines residual tree damage, soil disturbance (Pereira et al., 2002) and biodiversity loss (Burivalova et al., 2014) during tropical selective logging. The intensity of official logging in this study (5 trees ha^{-1} and 25.5 m^3 ha^{-1}) is relatively low compared with the maximum ranges reported in the tropics, such as 20 trees ha^{-1} (Picard et al., 2012), 70 m^3 ha^{-1} (Pereira et al., 2002) and 200 m^3 ha^{-1} (Burivalova et al., 2014). (Sist et al., 1998) suggested that the felling intensity of reduced-impact logging must be limited to a maximum of 8 trees ha^{-1} to reduce logging damage by 50% in comparison with conventional logging. Thus, the intensity of official logging in this case study may not be the main reason for forest degradation. However, the amount of illegal logging was substantial, and its volume (27.5 m^3 ha^{-1}) over the 5-year post-harvest period was similar to that of official logging. When we considered the total of human-induced disturbances, which included official road construction and collateral death caused from felling legally and illegally cut trees, the amounts of killed trees were similar between legal and illegal disturbances (29.3 and 28.0 m^3 ha^{-1}, respectively). The volume affected by illegal disturbances is considerably greater than the 5-year volume increase (1.45 m^2 ha^{-1}) resulting from natural occurrences (mortality, recruitment and living tree growth). Using data from only 5-year measurements, we could not determine whether stocking would recover to the pre-harvest level for the 30-year cutting cycle, but it was clear that illegal disturbances are the main cause of the large reduction in stocking after official logging (Figure 6.4).

Our field measurements confirm that illegal logging occurred after the official logging. Illegal logging has a large impact not only on stocking but also on species composition. The illegal logging targeted two of the most commercially important species, teak and Group 1 (*X. xylocarpa*). The mean DBH (± SD) of illegally cut teak and *X. xylocarpa* were 58.1 ± 16.9 and 49.1 ± 18.2, respectively, which are lower than the MDCLs (63 cm for *T. grandis* and 68 cm for *X. xylocarpa*) (Forest Department, 2015). Even though the official timber harvesting of *T. grandis* was not implemented at this study site, all the trees larger than the MDCL (63 cm), i.e., Class I, and all the trees of Class II, which are between 53 cm and the MDCL (63 cm), have been cut illegally (Figure 6.3). Thus, teak will not be available in the next cutting cycle. A similar situation was found for *X. xylocarpa* , most of which are in Class I and II, and were illegally cut (Figure 6.3).

6.4.2. Natural occurrences: Mortality, recruitment and living tree growth

Although mortality and recruitment may vary between species and diameter classes, the mean mortality rate (2.5%) in the present study was similar to, or well within the range of, reported values from tropical rain forests in the Amazon and Southeast Asia. Generally, the annual mortality rates range between 1% and 2% per year in non-logged natural tropical forests (Swaine et al., 1987), but the values were often higher for recently logged forests and tended to decrease over the years after timber harvesting. For example, Silva et al., 1995 reported mortality rates of 2.6%, 2.4% and 2.2% per year in Tapajós National Forest, at 5, 6 and 11 years after harvest, respectively. The highest mortality rates are observed during the first 2-year post-harvest period (Shenkin et al., 2015; Sist and Nguyen-Thé, 2002), and mortality rates stabilize later, between 7- and 11- (Dionisio et al., 2017), 5- and 10- (Sist and Nguyen-Thé, 2002) or after 15-years (de Avila et al., 2017) post-harvest.

The mean recruitment rate (3.1%) in the present study was greater than the 2.33% ± 0.13% (n = 32) and 1.75% ± 0.66% (n = 9) values reported for mature rain forests in the Amazon

Basin (Phillips et al., 2004) and Southeast Asia (Phillips and Gentry, 1994), respectively. The increasing intensity of logging results in more recruitment (Amaral et al., 2019). Thus, the large recruitment in this study may result from disturbances caused by both of legal and illegal logging. However, it should be noted that there were no and only 1.5 trees ha^{-1} requirements over 5 years for the first and second grade species teak nd *X. xylocarpa*, respectively, which were largely reduced by illegal and/or legal disturbance (Table S1). In contrast, more requirements were found in the least three grade species group (Table S1). Therefore, it may be difficult to harvest the high-grade timber species in the future, even though our results were obtained only over 5-year measurements.

The net changes in stocking from natural occurrences (natural mortality, recruitment and increment of living trees) over 5 years were small, since the gain from the increment was similar to the loss from the morality for all the species while the gain from recruitment was relatively small. This indicates that the changes from the natural occurrences is much smaller than those from legal and illegal human disturbances (Figure 6.4).

6.4.3 Diameter Increment

The diameter growth rate is an important parameter for calculating the AAC, and 0.32 cm $year^{-1}$ is currently adopted for the 30-year cutting cycle of the MSS. AAC is estimated based on the numbers of commercial trees in Class I, which represents the currently harvestable DBH class, being equal or more than the MDCL, and Class II, which can reach the MDCL within a 30-year cutting cycle. The DBH range of Class II is from MDCL to MDCL minus 10 cm, which is determined by the average growth rate multiplied by the cutting cycle (0.32 cm $year^{-1} \times 30$ years = 9.6 cm). For teak with an MDCL = 63 cm, Class I is > 63 cm and Class II is 53– 63 cm. Thus, if the currently adopted growth rate (0.32 cm $year^{-1}$) overestimates (or underestimates) the real growth, the Class II range and AAC are overestimated (or underestimated). Because the currently adopted value (0.32 cm $year^{-1}$) is significantly smaller than our finding (0.48 cm $year^{-1}$), the current AAC based on a growth rate of 0.32 cm $year^{-1}$ may not be an overestimation, but an underestimation.

However, growth rates in logged forests are highest during the early post-logging period owing to the increases in open space and sunlight available to residual trees, and growth rates have decreasing trends over time after logging. The highest growth rates occur at 5 years after harvest and gradually decrease to the level of the unlogged control area at 11-years post-logging in a Brazilian tropical forest (Dionisio et al., 2018) and 16-year post-logging in a Ghanaian high forest (Hawthorne et al., 2012). Therefore, the growth rate of 0.48 cm $year^{-1}$ from 5-year post-harvest measurements is likely overestimated as an average for the 30-year post-harvest period, and thus, the currently adopted value (0.32 cm $year^{-1}$) may not represent an underestimation for the 30-year cutting cycle.

6.5. Conclusions

There were similarities in stand dynamics components, such as disturbance from legal logging operations, natural mortality, recruitment and tree growth rates, between the previous studies in tropical forests and this study at a traditional forestry site in Myanmar. However, the magnitude (volume) of illegal logging is similar to that of legal logging and considerably larger than changes caused by the other components of stand dynamics. Illegal logging also causes dramatically decreasing numbers of large-size commercial trees, particularly teak and *X. xylocarpa*. Thus, illegal logging following legal logging is the most critical factor causing forest degradation, at least in terms of the provisioning services of the selectively logged production forest ecosystem. It should be cautioned that this study is based on data from the 5-year measurements, so longer term monitoring is essential to evaluate the sustainability of selectively logged production forests over 30-year cutting cycle.

Supplementary (Table S1)

Table S1. Changes in the density (trees ha^{-1}) of trees with DBH > 10 cm for all and each species group.

Years	All species			Species group (Mean of the subplots A and B)					
	Mean	Subplot		Teak	Group1	Group2	Group3	Group4	Group5
		A	B						
Stock in 2012 before legal operations	**176**	201	151	**22.5**	**16.5**	**10.0**	**26.5**	**10.5**	**90.0**
Legal disturbance in 2012	**-19.0**	-36.0	-2.00	**-1.50**	**-4.00**	**-0.50**	**-6.00**	**-0.50**	**-6.50**
Legal cut	-5.00	-8.0	-2.00	0.00	-2.50	0.00	-2.00	0.00	-0.50
Killed from legal-cut	-5.50	-11.0	0.00	-0.50	-1.00	0.00	-1.50	-0.50	-2.00
Killed from road construction	-8.50	-17.0	0.00	-1.00	-0.50	-0.50	-2.50	0.00	-4.00
Stock in 2012 after legal operations	**157**	165	149	**21.0**	**12.5**	**9.50**	**20.5**	**10.0**	**83.5**
Illegal disturbance from 2012 to 2017	**-24.0**	-26.0	-22.0	**-9.00**	**-4.50**	**-1.50**	**-1.50**	**-1.00**	**-6.50**
Illegal cut	-13.5	-17.0	-10.0	-9.00	-3.00	-0.50	0.00	0.00	-1.00
Killed from illegal-cut	-10.5	-9.0	-12.0	0.00	-1.50	-1.00	-1.50	-1.00	-5.50
Natural changes from 2012 to 2017	**5.00**	9.00	1.00	**-1.00**	**1.50**	**-0.50**	**3.00**	**2.50**	**-0.50**
Mortality	-19.5	-18.0	-21.0	-1.00	0.00	-1.50	-2.50	-2.00	-12.5
Recruitment	24.5	27.0	22.0	0.00	1.50	1.00	5.50	4.50	12.0
Stock in 2017	**138**	148	128	**11.0**	**9.50**	**7.50**	**22.0**	**11.5**	**76.5**

Supplementary (Table S2)

Table S2. Changes in basal area (m^2 ha^{-1}) of trees with DBH 10 > cm for all and each species group.

Years	All species			Species group (Mean of the subplots A and B)					
	Mean	Subplot		Teak	Group1	Group2	Group3	Group4	Group5
		A	B						
Stock in 2012 before legal operations	**16.6**	16.3	16.8	**3.25**	**2.83**	**0.65**	**2.47**	**2.18**	**5.19**
Legal disturbance in 2012	**-3.62**	-5.48	-1.75	**-0.02**	**-1.81**	**-0.01**	**-1.26**	**-0.10**	**-0.42**
Legal cut	-2.91	-4.07	-1.75	0.00	-1.71	0.00	-1.08	0.00	-0.12
Killed from legal-cut	-0.37	-0.75	0.00	-0.01	-0.03	0.00	-0.07	-0.10	-0.17
Killed from road construction	-0.33	-0.66	0.00	-0.01	-0.07	-0.01	-0.11	0.00	-0.13
Stock in 2012 after legal operations	**12.9**	10.8	15.1	**3.24**	**1.01**	**0.64**	**1.21**	**2.07**	**4.77**
Illegal disturbance from 2012 to 2017	**-3.57**	-3.32	-3.82	**-2.54**	**-0.75**	**-0.08**	**-0.03**	**-0.07**	**-0.10**
Illegal cut	-3.34	-3.09	-3.60	-2.54	-0.73	-0.06	0.00	0.00	-0.01
Killed from illegal-cut	-0.23	-0.24	-0.22	0.00	-0.02	-0.02	-0.03	-0.07	-0.09
Natural changes from 2012 to 2017	**0.16**	0.44	-0.12	**0.07**	**0.11**	**-0.06**	**0.08**	**-0.11**	**0.08**
Mortality	-1.28	-0.93	-1.63	-0.05	0.00	-0.13	-0.12	-0.36	-0.61
Recruitment	0.30	0.28	0.33	0.00	0.02	0.01	0.06	0.08	0.14
Increament of living trees	1.13	1.09	1.18	0.12	0.09	0.06	0.14	0.17	0.55
Stock in 2017	**9.54**	7.95	11.1	**0.77**	**0.37**	**0.51**	**1.25**	**1.89**	**4.74**

Supplementary (Table S3)

Table S3. Annual DBH increment (cm $year^{-1}$) for species group.

Species group	Mean	95% confidence interval		p-value from t-test comparison with 0.32 cm	Sample size
		Lower	Upper		
Teak	0.54	0.43	0.66	<0.001	20
Group1	0.69	0.61	0.78	<0.0001	16
Group2	0.46	0.20	0.72	0.26	13
Group3	0.39	0.30	0.49	0.11	33
Group4	0.55	0.38	0.73	0.01	14
Group5	0.46	0.40	0.51	<0.0001	126
All	0.48	0.44	0.52	<0.0001	222

Supplementary (Table S4)

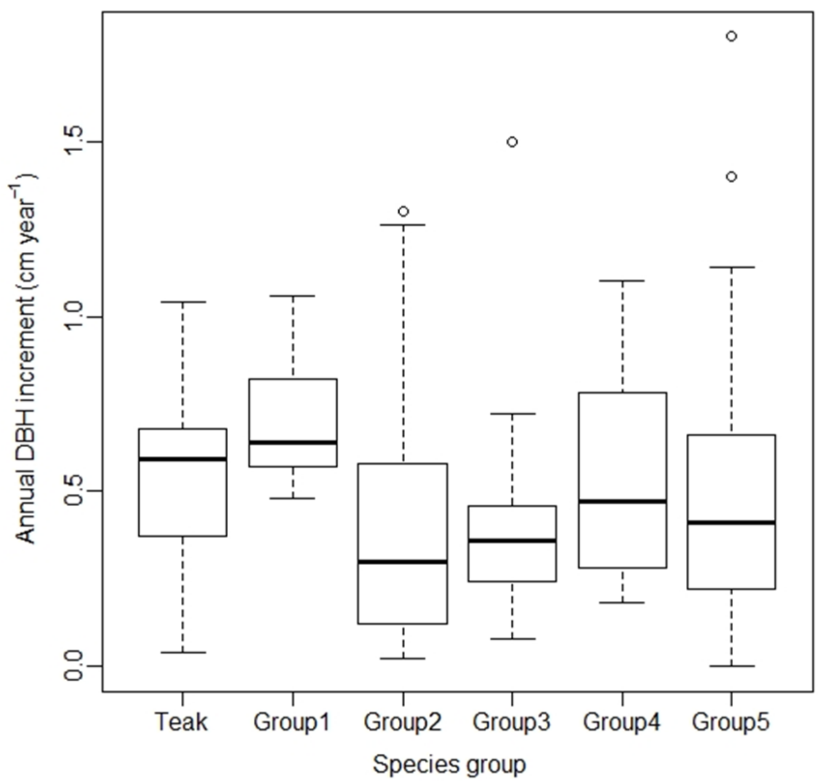


Figure S1 Annual DBH increment for each species group

Chapter 7

General discussion and conclusion

The terms "Myanmar selective logging" or "MSS" used in this study referred to the official selective logging which was conducted by the MTE under the timber harvesting plans of FD. This study with its theme on evaluating the human disturbances and stand dynamics in selectively logged production forests is therefore limited to the ecological impacts of logging disturbance to production forests legally classified as RF under the category of the PFE. At first, the study evaluated the level of harvesting intensity and logging disturbances under the MSS operations, and then evidences of the importance of following 30-year felling cycle is shown by comparing stand density and compositions of two compartments subjected to different cutting frequencies. Finally, based on five-year field data, the logging disturbances from legal and illegal activities and their impacts to post harvest stand dynamics was revealed in this study.

7.1 Harvesting intensity regulated by minimum diameter cutting limit (MDCL)

In the context of tropical selective logging, the harvesting intensity is one of the critical factors determining the logging disturbances from which recovery of the logged-over will be further determined. Under the MSS, the annual yield known as AAC, like as many other selective logging in the tropics, is fixed by the inventory at a nationwide scale and at the very timber extraction site, all commercially trees species ≥ MDCL were marked for selection felling. As expected, the results of this study revealed that harvesting intensity operated at the MDCL system considerably vary ;1.4 to 4.2, 4.8 and 10.2 tree ha $^{-1}$ respectively at the sampling plot (9-ha) level. Presumably, production forests with higher tree density will yield higher harvestable trees i.e. harvesting intensity. An opposite trend or abnormal pattern was evidenced as despite having lowest tree density (121.5 trees ha^{-1}) in Site 4, the harvesting intensity is highest with average 10.2 tree ha^{-1}ranging from 4 tree ha^{-1} (46.5 m^{3}) to 18 tree ha^{-1} (143.7 m^{3} ha^{-1}). This figure, 121.5 trees ha^{-1} is even distinctly smaller than the 140 tree ha^{-1} in Yedashe, Myanmar where forest degradation largely occurred (Win et al., 2018a). Indeed, extraction of 8.4% of total stock at a single successive logging is not small. The extraction rate is even much substantial in term of basal area; 40 % of total stocks, as biggest size trees ≥ MDCL were extracted. Apart from the legal harvesting, we also encountered illegal cut trees, 6.1 trees ha^{-1}. These illegal stumps, mostly *Tectona grandis* with average size 65.05 ± 12.25 cm were cut recently. By assuming there were no illegal cutting, the average harvesting intensity at Site 4 might exceed > 15 trees ha^{-1}, as high as those reported values of dipterocarps forest in Southeast Asia (Sist et al., 1998; 2003; Putz et al., 2008). From this study, the figures obtained from a total of 36-ha plots have obviously revealed that selective logging conducted at MDCL rule of MSS alone has tendency of high harvesting intensity. (Chapter 3).

7.2. Logging induced disturbances

Forest damage resulting from selective logging operations can be divided into the general categories of residual tree damages, ground disturbances and canopy cover reductions. This study focused on the residual trees damage resulted from felling of trees, which can damage or kill surrounding trees and vegetation and disturb regeneration, and ground-area disturbance resulting from the construction and use of logging roads, skid trails and log landings and additional disturbed area by machine maneuvering.

The residual damaged tree (%) induced at tree felling operation during one successive logging ranges from 1.4 - 22% of total tree. Similarly, the total ground disturbances (road, log landing, skid trial, machine disturbed area) at post-logging ranges from 2.4 – 11.6 % of the total area. Both of residual tree damage rate and ground damage are certainly scaled with the harvesting intensity as shown as in numerous studies across the tropics. Chapter 3 revealed that percentage of both the residual damaged trees and ground disturbance against felling intensity under MSS were the lowest compared to cases in other tropical forests, and judged the exceptional utilization of elephants in log skidding operation is the main advancement for the MSS (Khai et al., 2016; Lin, 2006). In this case, caution must be taken that logging damage under MSS are in the lowest level if compared with the same range of harvesting intensities across other studies. It did not necessarily imply that the ecological impact of selective logging under MSS were all low but depending on the harvesting intensity. This is the case particularly in Site 4 (Gaingshi RF); when felling intensity exceeded 10 trees ha^{-1} (~100 m^3 ha^{-1}), the accumulated ground disturbances from forest road, log landings and extra machine disturbed areas achieved ~12% of the total area. This extent is not small, higher than those commonly reported values for RIL studies (regardless of the harvesting intensity). In this case of high felling intensity observed in Site 4, more than one-third of the total harvested trees, mostly *Dipterocarpus species* (*Kanyin*), have DBH >100 cm. Elephant power mainly used in the skidding operation has certain limitations. Such as high felling intensity both in terms of size and quantity resulted to aid machine in skidding operations, which subsequently increased the logging disturbance level.

The tendency of over logging by the MDCL rule and the high felling intensity in significant relation to logging damage in SE Asian dipterocarp forests have been well reported (Putz et al., 2008, Sist et al., 1998, 2003). However, this study, may be the first instance to record evidence of high felling intensity by the MDCL under MSS. It seems that either the harvesting intensity or the subsequent damages induced at the logging operations has been a neglected issue in the MSS or presumed inherently low harvesting; 2-3 trees ha^{-1} or < 20 m^3 ha^{-1} (Kermode.,1964; Gyi and Tint., 1998). This presumption of timber harvesting intensity may somewhat accord with logging where dipterocarp species are not common such as in Bago Yoma which has been under fallow period. At the national scale, the timber harvesting plan implemented in fiscal year 2017-2018 was only 55% of teak and 33% of non-teak hardwood, respectively than the prescribed AAC. Production forests in Katha region including Site 4 (Gaingshi RF) was one of the main extraction sites in 2017. In site 4, when the timber extraction plan was completed, the logged-over forest (Site 4) was left with only 105 residual trees ha^{-1}, about 12% of the top soil being removed, and *Chromolaena odoratum*, a weedy exotic species already intruded in some gaps and along the logging road. Such condition of logged over production forest exhibited that the harvesting intensity regulated only by the MDCL rule is risky in consideration of the damage and integrity of forest functions that need to maintain over the next felling cycle to ensure the sustainability. Studies at mixed dipterocarp forests in SE Asia showed a maximum extraction rate of 8 trees ha^{-1} (80 m^3 ha^{-1}) is recommended to lessen tree damage level by 50% (Sist et al., 1998, 2003a). Extraction of all trees attaining the MDCL will be too destructive in the short term and will lead the shortage of mature trees on the long term. Thus, harvesting trees selected based solely by prescribed MDCL under MSS need to be modified so as to adopt suitable felling intensity compatible with minimum damage level. Within the data range from this study, we are incapable to suggest the range of harvesting intensity limit. In light of the fact that the relatively low damage of MSS is mainly due to the use of elephants' power for skidding while elephant skidding is unsuitable for large trees and/or in areas on steep slopes, a reasonable suggestion would be to avoid harvesting of large trees that cannot be dragged by elephants. Rule of MDCL as well as maximum diameter cutting limit would be ideal as big trees that may be functioned as seed source and for biodiversity conservation will be retained.

7.3. Past disturbance /repeated cutting

The sampling plots of this study were established at two legendary forestry regions; Bago in lower central Myanmar and Katha situated in the upper central Myanmar, within the territory of mixed deciduous forests type. Topographically, the sampling site (Site 1) at South Zamaye RF, Bago and sampling site (Site 4) at Gaingshi RF, Katha, situated in upper north and lower south respectively, are in moist deciduous forests area and close to the fringe of semi-evergreen forest types. The other two sampling sites (Site 2 and Site 3) in Pyinde RF of Katha are situated in somewhat a drier terrain. In term of species composition, *Tectona grandis* was the predominant species at all sites. In Gaingshi RF site in the most northern site, *Xylia xylocarpa* and Dipterocarpus species (Kanyin) were found to be abundant as associate of *Tectona grandis*. In the two sites in Pyinde, *Xylia xylocarpa* was absent and, instead other commercial species including *Pentacme siamensis* (Ingyin), *Protium serrata* (Thadi), *Terminalia tomentosa* (Taukkyant) and *Adina cordifolia* (Hnaw) are found with bamboo species of *Thyrsostachys oliveri* (Thanawa) and *Cephalostachyum pergracile* (Tinwa) in the intermediate layer but with much less extent compared to that of bamboos in South Zamaye and Gaingshi sites. (Table 3.1). In term of species composition, forests in the four sampling sites seemed to be not in abnormal condition pertaining to their respect forest types. In term of tree density, however, South Zamaye and Gaingshi sites being in moister regions are expected to bear higher density. In actual, lower number of tree densities of these two moister sites (176 trees $ha^{-1}$and 121.5 ha^{-1}) than the Pyinde sites (198.5 trees $ha^{-1}$and 254 trees ha^{-1}) is hard to rationalize from the ecological aspect. A possible factor which could tangibly accused of is that *partial hardwood extractions* by the private company was conducted in both sites; South Zamaye and Gaingshi RF. Such *partial hardwood extractions* might be granted official permission, but were rarely well documented. Even, it is unsure if such past logging disturbances were taken into account when the felling cycle of timber harvesting plan is regulated. In the field, the old stumps of such *partial hardwood extractions* were easily recognizable for premium hardwood species with giant size and height ≥ 100 cm, often in ease accessible areas. Such harvesting typically focused only on a few premium hardwoods (Group 1), and thus the felling intensity in term of tree number per ha would be low. However, what remains unknown was the extent of logging damage which would be induced for felling of such giant trees. Perceivably, the use of machine will be indispensably needed in extraction of such premium trees. In a worse case, as in Site 4 (Gaingshi RF), illegal logging as high in logging intensity as the legal logging intensity was followed, and undoubtedly the residual trees would only be left behind with additional disturbances again. This phenomenon of vicious cycle exactly exhibits the real condition of production forest as well as indicating the underlying factor causing degradation of the production forests in Myanmar.

7.4. Impact of human disturbance on stand dynamics

In its natural forms, the tropical deciduous forests are a mixed crop of trees of various species intermingling with vast stretch of bamboo (Keh., 1993). Normally, the composition of *Tectona grandis* varies up to 20 %, *Xylia xylocarpa* 10-30 %, and other species seldom exceeding 3% (Watson., 1923; Tint., 2018). Due to both legal and illegal logging disturbance, the composition of *Tectona grandis* and *Xylia xylocarpa* have decreased from 12.78 to the lower marginal 7.94 %, and 9.38 to 6.50 % of residual stocks, respectively at post 5-year harvest level. These two main indicator and predominated species of the site at pre-harvest level have been replaced in their role by *Derris robusta* (LUS) and *Lagerstroemia speciosa* (Group II). On the other hand, *Duabanga grandiflora* (Group IV) was emerged as newly recruited species from logging gap to occupy 2.89 % of the growing stocks (*Supplementary; Appendix I*). There have been certain changes in species composition of the logged over forest, shifting devaluation. Logging road which occupied 4.6 % of the total area (Khai et al., 2016) could have further effect on the logged forest (Ne Win., 2011; Katovai et al., 2016) as different forest functional traits likely appeared in the secondary succession stage. Apart from lacking future yield after the incidence of illegal tree cutting at logged over forest, generation capabilities of the long term will be of great concern as no mother seed trees of teak and Xylia xylocarpa remain in standing residual stocks. Fecundity of flowering trees is size related (Whitmore., 1984). Even when mature trees are present, reproduction could still have limitation. As of instance, *Xylia xylocarpa* appears to flower freely every year but does not produce seeds regularly. The fragile flowers could still be destroyed by the heavy pre-monsoon showers taking place at the time when *Xylia xylocarpa* was flowering (Kermode, 1964). For teak, light is one of the factors for growth and recruitment of regenerations. In the Myanmar teak bearing forests, canopy opening by logging is highly correlated with the recruitment of teak regenerations but with the presence of mother trees (Ne Win., 2011). In fact, scarcity or poor regeneration and smaller size trees, especially for teak and valuable tree species is an existing problem (Keh., 1993) in the mixed deciduous forests in Myanmar production forests.

To retain seed mother trees in forests where the stocking of teak is poor is a standard in the MSS (Gyi and Tint., 1998). However, the precise silvicultural instruction seems to be lacking. From the logging disturbance aspect, the residual tree damage particularly severe damage was dependent on the size of felled tree (Chheng et al.,2015). Chapter 3 has further confirmed this point from case studies conducted in semi-evergreen forest in Cambodia and tropical mixed deciduous forest of Myanmar. Thus, avoiding felling of large trees will be an encouragement as it will insure against a decline in mother seed trees and preserve a valuable part of the habitat, in addition to considering the largest damage that will be caused when felled (Khai 2013). Beside, very large individual trees often have structural defect that reduce their timber value (Sist et al., 2003a). Moreover, felling larger size trees create larger combine gap which favour pioneer species regeneration. The MSS, originally modified from the Brandis yield model, is suitable to apply for forest with sufficient amount of mature trees in the original stock (Osmaston., 1984). In practicing this yield model, sufficient mature trees for the second harvest will have left after the first harvest. However, at the prevailing condition of degradation, the number of tree left were greatly declining and eventually resulting to scarcity of mature trees for the second felling cycle.

7.5. Conclusion

From the evidence obtained from this study, it can be concluded that the logging damage under the MSS operations were at lower level compared to those reported values, but depending on the harvesting intensity, and the harvesting intensity regulated only by the MDCL rule has a tendency toward overexploitation. The logged-over forests with annual growth rate 0.48 cm ha^{-1} could have a positive trend to recover. However, the illegal logging triggered by forest logging road constructed under MSS operation has largely increased the vulnerability of the newly logged forests and has substantial impact to the growing stocks. In conclusion, human disturbances in terms of repeated loggings faster than the standard felling cycle with accompanying illegal logging be the most detrimental factor for the degradation of the production forests. It is recommended to limit the harvesting intensity in terms of quantity and size of harvested trees to reduce the impact on residual trees and ground. It is also crucial to decommission the forest roads after the operation to combat illegal logging in the logged over forests.

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Appendix I

Appendix : Supplementary material

Comparison of most abundant 10 tree species between pre-harvest and post 5-year harvest level

Species	Pre-harvest stocks Rank	Pre-harvest stocks Tree number (n/ha)	Pre-harvest stocks Mean DBH (cm ± SD)	Pre-harvest stocks Relative density (%)	Post 5-year harvest stocks Rank	Post 5-year harvest stocks Tree number (n/ ha)	Post 5-year harvest stocks Mean DBH (cm ± SD)	Post 5-year harvest stocks Relative density (%)	Diameter Increment rate (cm/ year)	Species Group
Tectona grandis Linn.	1st	22.5	36.51 ± 20.92	12.78	3rd	11	27.95 ± 10.61	7.94	0.54 ± 0.25	Teak
Xylia xylocarpa	2nd	16.5	36.34 ± 29.77	9.38	6st	9.5	20.80 ± 8.43	6.86	0.69 ± 0.16	Gr I
Lagerstroemia speciosa	2nd	16.5	21.32 ± 9.75	9.38	2th	13	19.8 ± 9.07	9.39	0.39 ± 0.29	Gr III
Derris robusta	2nd	16.5	24.50 ± 13.47	9.38	1st	15.5	26.34 ± 13.77	11.19	0.34 ± 0.24	Gr V
Stereospermum grandifolium	5th	11.5	23.99 ± 19.00	6.53	3rd	11	24.23 ± 19.16	7.94	0.40 ± 0.25	Gr V
Dillenia pentagyna	6th	8	26.03 ± 14.91	4.55	8th	4.5	29.79 ± 18.01	3.25	0.45 ± 0.23	Gr V
Milletia brandisiana	7th	7	18.53 ± 8.94	3.98	5th	8	19.41 ± 9.90	5.78	0.68 ± 0.33	Gr V
Terminalia chebula	8th	5	30.37 ± 10.81	2.84	8th	4.5	31.89 ± 11.61	3.25	0.40 ± 0.19	Gr III
Salmalia insignis	8th	5	32.99 ± 15.33	2.84	10th	4	34.69 ± 18.94	2.89	0.55 ± 0.29	Gr IV
Mitragyna rotundifolia	10th	4.5	23.04 ± 18.37	2.56	*	*	*	*	*	Gr II
Dalbergia ovata	10th	4.5	19.99 ± 5.74	2.56	7th	5	20.58 ± 6.43	3.61	0.55 ± 0.29	Gr V
Duabanga grandiflora	*	*	*	*	10th	4	15.24 ± 3.62	2.89	nil	Gr IV

* Not included in top 10 abundant species

Appendix II

Individual trees species recorded at pre-harvest to 5-years after selective logging in Zamaye RF, Bago Yoma ,Myanmar

Local Name	Species	Family	Commercial / Lesser used species	Pre-harvest (n/ha)	(%)	Post 5-year (n/ha)	(%)	Net (-)/(+) % of pre-harvest
Kyun	Tectona grandis	Verbenaceae	Comm.	22.5	12.8	11	7.9	(-) 51.1
Pyinkado	Xylia xylocarpa	Mimosaceae	Comm	16.5	9.4	9.5	6.9	(-) 31.1
Pyinma	Lagerstroemia speciosa	Lythraceae	Comm	16.5	9.4	13	9.4	(-) 15.6
Didu	Salmalia insignis	Bombaraceae	Comm	5	2.8	4	2.9	(-) 4.4
Panga	Terminalia chebula	Combretaceae	Comm	5	2.8	4.5	3.2	(-) 2.2
Binga	Mitragyna rotundifolia	Rubeaceae	Comm	4.5	2.6	2.5	1.8	(-) 8.9
Taukkyant	Terminalia tomentosa	Combretaceae	Comm	3	1.7	2	1.4	(-) 4.4
Thadi	Protium serratum	Burseraceae	Comm	2.5	1.4	2.5	1.8	(=) 0
Gwe	Spondias pinnata	Anacardiaceae	Comm	2.5	1.4	0.5	0.4	(-) 8.9
Yon	Anogeissus acuminata	Combretaceae	Comm	2	1.1	2	1.4	(=) 0
Yindaik	Dalbergia cultrata	Fabaceae	Comm	2	1.1	1.5	1.1	(-) 2.2
Thitmagyi	Albizia odoratissima	Minosaceae	Comm	1	0.6	1	0.7	(=) 0
Baing	Tetrameles nudiflora	Datiscaceae	Comm	1	0.6	1.5	1.1	(+) 2.2
Chinyok	Garuga pinnata	Burseraceae	Comm	0.5	0.3	0.5	0.4	(=) 0
Taungtayet	Swintonia floribunda	Anacardiaceae	Comm	0.5	0.3	0.5	0.4	(=) 0
Myaukngo	Duabanga grandiflora**	Lythraceae	Comm	nil	nil	4	2.9	(+) 17.8
Kanaso	Baccaurea sapida**	Euphorbiaceae	Comm	nil	nil	0.5	0.4	(+) 2.2
Pokthima Myetkauk	Derris robusta	Fabaceae	LUS	16.5	9.4	15.5	11.2	(-) 4.4
Thande	Stereospermum personatum	Bignoniaceae	LUS	11.5	6.5	11	7.9	(-) 2.2
Zinbyun	Dillenia pentagyna	Dilleniaceae	LUS	8	4.5	4.5	3.2	(-) 15.6
Thitpagan	Milletia brandisiana	Fabaceae	LUS	7	4.0	8	5.8	(+) 4.4
Madama	Dalbergia ovata	Fabaceae	LUS	4.5	2.6	5	3.6	(+) 2.2
Seikchi	Bridelia retusa	Euphorbiaceae	LUS	3.5	2.0	2	1.4	(-) 6.7
Thetyingyi	Croton oblongifolius	Euphorbiaceae	LUS	3	1.7	1	0.7	(-) 8.9
Konpyinma	Lagerstroemia macrocarpa	Lythraceae	LUS	3	1.7	3	2.2	(=) 0
Zaungpalwe	Lagerstroemia villosa	Lythraceae	LUS	3	1.7	2	1.4	(-) 4.4
Shaw	Sterculia species	Sterculiaceae	LUS	3	1.7	2.5	1.8	(-) 2.2
Linnyaw	Dillenia parviflora	Dilleniaceae	LUS	2.5	1.4	1	0.7	(-) 6.7
Thitpok	Dalbergia kurzii	Fabaceae	LUS	2	1.1	1	0.7	(-) 4.4
Gyo	Schleichera oleosa	Sapindaceae	LUS	2	1.1	2	1.4	(=) 0
Phetwun	Berrya ammonilla*	Tiliaceae	LUS	1.5	0.9	nil	nil	(-) 1.5
Yinzat	Dalbergia fusca	Fabaceae	LUS	1.5	0.9	0.5	0.4	(-) 4.4
Thabutgyi	Miliusa velutina	Annonaceae	LUS	1.5	0.9	1	0.7	(-) 2.2
Mayanin/Yetama	Acrocarpus fraxinifolius	Pittosporaceae	LUS	1	0.6	0.5	0.4	(-) 2.2
Thanthat	Albizia lucida	Minosaceae	LUS	1	0.6	1.5	1.1	(+) 2.2
Thanat	Cordia dichotoma	Boraginaceae	LUS	1	0.6	1.5	1.1	(+) 2.2
Tayaw	Grewia tiliaefolia	Tiliaceae	LUS	1	0.6	1.5	1.1	(+) 2.2
Kyetsu	Jatropha curcas	Euphorbiaceae	LUS	1	0.6	0.5	0.4	(-) 2.2
Nabe	Lannea grandis	Anacardiaceae	LUS	1	0.6	1	0.7	(=) 0
Kyaungsha	Oroxylum indicum	Bignoniaceae	LUS	1	0.6	1	0.7	(=) 0
Wuttharkhauk	Unclassified *Wuttherkhauk* 0	Unclassified 01	LUS	1	0.6	0.5	0.4	(-) 2.2
Magyipauk	Sapindus saponaria	Sapindaceae	LUS	1	0.6	0.5	0.4	(-) 2.2
Kyetyo	Vitex pubescens	Verbenaceae	LUS	1	0.6	1	0.7	(=) 0
Ngu	Cassia fistula	Caesalpiniaceae	LUS	0.5	0.3	0.5	0.4	(=) 0
Aukchinsar	Diospyros ehretioides*	Ebenaceae	LUS	0.5	0.3	nil	nil	(-) 0
Zibyu/shaphyu	Emblica officinalis	Euphorbiaceae	LUS	0.5	0.3	1	0.7	(+) 2.2
Kathit	Erythrina suberosa	Fabaceae	LUS	0.5	0.3	0.5	0.4	(=) 0
Naywe	Flacourtia cataphracta	Flacourtiaceae	LUS	0.5	0.3	0.5	0.4	(=) 0
Thittayaw	Grewia spp	Tiliaceae	LUS	0.5	0.3	0.5	0.4	(=) 0
Lettokgyi	Holarrhena antidysenterica	Apocynaceae	LUS	0.5	0.3	1	0.7	(+) 2.2
Myaukchaw	Homalium tomentosum	Flacourtiaceae	LUS	0.5	0.3	0.5	0.4	(=) 0
Dwabok	Kydia calcina*	Malvaceae	LUS	0.5	0.3	nil	nil	(-) 0.5
Mahlwa	Markhamia stipulata	Bignoniaceae	LUS	0.5	0.3	0.5	0.4	(=) 0
Taungkyunbo	Premna pyramidata	Verbenaceae	LUS	0.5	0.3	0.5	0.4	(=) 0
Che	Semecarpus anacardium	Anacardiaceae	LUS	0.5	0.3	0.5	0.4	(=) 0
Unknown TN 221	Unknown 02	Unclassified 02	LUS	0.5	0.3	0.5	0.4	(=) 0
Unknown TN 68	Unknown 03*	Unclassified 03*	LUS	0.5	0.3	nil	nil	(-) 0.5
Thaphan	Ficus chittagonga**	Moraceae	LUS	nil	nil	0.5	0.4	(+) 2.2
Phetthan	Haplophragma adenophylla**	Bignoniaceae	LUS	nil	nil	0.5	0.4	(+) 2.2
Leza	Lagerstroemia tomentosa**	Lythraceae	LUS	nil	nil	0.5	0.4	(+) 2.2
				176		138.5		**(-)** 21.3

* = Disappeared species

** = Ingrowth tree species

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