Five-year changes in forest use and stand structure in illegally logged production forests in Myanmar

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Doctor of Philosophy (Ph.D.)

By

Thein Saung

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Abbreviations

ANOVA	Analysis of Variance
DBH	Diameter at Breast Height
DF	Degree of Freedom
ELC	Economic Land Concession
FAO	Food and Agriculture Organization of the United Nations
FD	Forest Department
FRA	Global Forest Resources Assessment
GLM	Generalized Linear Model
Ha	Hectare
Km2	Square kilometer
LM	Linear Model
LUS	Lesser Used Species
M	Meter
MDCL	Minimum Diameter Cutting Limit
MM	Millimeter
MMK	Myanmar Kyat
MRRP	Myanmar Reforestation and Rehabilitation Programme
MSS	Myanmar Selection System
MTE	Myanmar Timber Enterprise
NTFPs	Non Timber Forest Products
PAs	Protected Areas
PFE	Permanent Forest Estate
PPF	Protected Public Forest
RF	Reserved Forest
SD	Standard Deviation
SEM	Structural Equation Modeling
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
VIF	Variance Inflation Factor

Summary

Global concern to maintain ecosystem services and sustainability of selectively logged production forests, about 20% of world's tropical forests, is growing under the occurrence of deforestation and forest degradation in the forests. Human disturbances co-occurring with selective logging is assumed as current global threat to tropical forests. Myanmar's selectively logged production forests, about 59.4% of the country's forest area, are under the threat of human disturbances and being experienced deforestation and forest degradation. Most studies focused on improving logging practices from ecological perspective to certain sustainability of production forests without considering the effect of illegal logging following legal logging practice. This study aims to observe changes of people's dependency, in terms of dependence level for cash income and forest use strategies, on selectively logged forests over time, and impacts of illegal logging on stand dynamics in selectively logged production forests using the time series data. Bago township, the southeastern part of Bago Yoma, Myanmar was selected as the study area, considering the long history of timber production in Bago Yoma, and 10 years logging ban practice for Bago Yoma since 2016.

To fulfill the main objective, firstly ***Chapter 2*** aimed to detect differences in forest use strategies and forest cash income dependency between households living outside and inside selectively logged production forests, known as Reserved Forests (RFs), in Bago Township, Myanmar. A questionnaire survey was conducted with 146 and 48 households living outside and inside the RFs, respectively. The inside-households (encroachers) had a much higher forest cash income dependency (83%), with charcoal production as the main forest use activity, than the outside-households (32%), with bamboo cutting as the main activity. Higher forest dependency was found for outside-households that had less farmland, better accessibility to forest and more recognition of prohibited access to RFs in forest law. This study revealed evidence of substantial forest use for commercial purposes in RFs by households living both inside and outside the RFs, despite local recognition of the illegality of the use. Implementing community forestry practices for local communities may be a better option to reduce illegal dependence on selectively logged production forests.

To understand dynamic of dependency on production forests following logging ban practice, secondly **C*hapter 3*** detected changes in cash income strategies and

dependence on forest income using time series data collected in 2013 and 2018, prior to and after, respectively, a logging ban was introduced for households adjacent to selectively logged production forests known as reserved forests (RFs) in Bago Township in Myanmar. A questionnaire was administered to 146 and 123 households in 2013 and 2018, respectively. The responses revealed that cash income from forests fell from an average of 588 USD to an average of 198 USD per year over the 5-year period, while non-forest cash income did not change significantly. Thus, the proportion of total household income accounted for by cash income from forests decreased from 32% to 21%. Both cash income from forests and the proportion of total income it accounted for were negatively correlated with farmland area and positively correlated with access to forests, but not correlated with knowledge about the logging ban. Thus, I conclude that reduced access to RFs following the logging ban was the main reason for the reduction in both forest income and the proportion of total income it accounted for. However, the level of dependence on forest income was not as low as that in other countries, even though the logging ban prohibited local people from using RFs to generate cash income. Thus, rural development projects are needed to provide increased opportunities for income generation, while extension activities are also required to increase the effectiveness of policies such as the logging ban.

To understand the conditions of illegally logged stands in selectively logged production forests, thirdly ***Chapter 4*** made observation in production forests experienced inappropriately short rotations between legal logging cycles. Four rectangular plots (each 0.64 ha) were established in 2013. The plots included illegally logged stumps in three compartments where the latest legal logging was conducted in 2011 after very short rotations between legal logging cycles (up to five harvests between 1995 and 2011, compared with a recommended 30-year logging cycle). Using data from the field measurements in 2013 on the legal and illegal stumps and living trees, I reconstructed stand structure just before and after legal logging in 2011. Before the legal logging in 2011, there were variations in stand structure and the composition of commercial species among four plots. Illegal logging (14–31 trees ha^{-1}) was much higher than legal logging (0–11 trees ha^{-1}). Illegal logging targeted six to nine species that were suitable for high-quality charcoal from various sized trees, while legal logging targeted one or two timber species with a diameter at breast height (DBH) larger than 58 cm. The number of remaining trees in 2013 ranged from 33 to 181 trees ha^{-1}. There was a negative relationship with the number of bamboo clumps, which varied from 6 to 145 clumps ha^{-1}. Bamboo-dominated stands with a low remaining stock of commercial trees may need active restoration such as bamboo cutting and replanting of commercial species. Bamboo cutting could generate income for the local community.

To understand the stand dynamics of illegally logged production forests over time, fourthly ***Chapter 5*** revealed an evidence of changes in stand structure between 2 and 7 years after legal logging and tree–bamboo–regeneration associations in illegally logged production forests in Myanmar. Variables in four square plots (each 0.64 ha) were measured twice, in December 2013 and December 2018. The plots included illegally and legally logged stumps in three compartments where legal logging was last conducted in 2011, after inappropriately high-frequency cycles of legal logging. Over the 5 years, substantial illegal logging continued to occur in two of the plots which had higher stocks. Tree density and basal area slightly increased and decreased, respectively, but bamboo increased rapidly by 267%, from 56 to 205 clumps ha^{-1} as the plot means. At the subplot level (size = 0.04 ha, n = 64), structural equation modeling indicated that tree density was negatively associated with bamboo stocks, and in turn, bamboo basal area was negatively associated with the number of regenerated trees. I conclude that a reduction in tree density owing to repeated legal and illegal logging can indirectly lead to smaller number of regenerated trees because of increasing amounts of bamboo. Bamboo cutting should be legally encouraged to restore bamboo-dominant, degraded stands as well as to improve local livelihoods.

In conclusion, rural people living outside and inside the production forests depended on the forests for cash income, though most of them have knowledge about the prohibited matter. Charcoal production was found as main forest use activity for the encroachers, while bamboo cutting was for the people living outside the production forest. Their dependency level and forest cash income reduced, accordingly total household income reduced after logging ban. Worse accessibility to forests was the main factors for reducing forest dependency. This study suggests to promote community forestry for sustainable charcoal production.

Frequent legal logging following illegal logging made substantial reduction of stocks in selectively logged production forest. Accordingly bamboo dominated in illegally logged production forests with negative relationship with density of remaining stocks. Reduced tree density indirectly caused less tree regeneration through increasing

bamboos. Illegal logging continued for 7 years after legal logging in more stocked stands. Bamboo were substantially increased over time consistently in all the stands. This study called for urgent action of cutting bamboo in degraded forests. In this concerns, sharing the legal right to rural people to cut bamboo and other NTFPs within production forest for cash income to have benefit not only for restoring the forest but also improving rural livelihood.

Chapter 1

General Introduction

1.1. Background information

Tropical forests, representing about 44% of the world's forest areas, provide ecosystem services and basic needs for millions of forest dependents around the world (Keenan et al., 2015). About 20% of the world's tropical forests are production forests, and selective logging is a commonly practiced forest management system (Blaser et al., 2011; Edwards et al., 2014; Putz et al., 2012). Tropical production forests supply both timber and non-timber forest products (Guariguata et al., 2010; Rist et al., 2012), main sources for the world's timber demand. Moreover, the conservation value of this forests becomes global concern (Berry et al., 2010; Edwards et al., 2014; Putz et al., 2012).

Selective logging operation itself can maintain sustained yields of timber volume over the long run, and it usually does not reduce canopy cover to less than 10%, which is a widely used threshold to distinguish forest from non-forest (Mon et al., 2012). However, selectively logged production forests have experienced degradation due to over-harvesting and/or large disturbances to the remaining trees and the ground (Asner et al., 2006; Mon et al., 2012; Pereira et al., 2002; Sasaki and Putz, 2009). Human disturbances co-occurring with selective logging is assumed as current global threat to tropical forests (Peres et al., 2006).

In effort to ensure sustainability of tropical production forests, most studies paid more attention on improving logging practices, such as adopting Reduced Impact Logging (RIL) (Rivett et al., 2016; Rosa Darrigo et al., 2016), limiting felling intensity following Minimum Diameter Cut Limit (MDCL) (Khai et al., 2020a; Sist et al., 1998), following felling cycle estimated based on growth increment (Khai et al., 2016). However, most of these studies paid attention on silvicultural perspective without considering illegal logging following legal logging in production forests. Limited studies revealed the higher felling intensity of illegal logging in selectively logged production forests (Khai et al., 2016; Win et al., 2018d).

Though it is possible to adjust felling intensity, felling cycle, and logging damage by improving logging practices to ensure sustainability, illegal logging is related with the socio-economic condition of forest dependent people, especially in tropical developing countries. About1.6 billion people around the globe substantially depend on forests for their livelihoods (World bank, 2004). Generally, forest managers practice law enforcement in controlling illegal activities, but other studies highlighted that law enforcement and limiting access to forest resources cannot solve the problem of illegal activities (Studsrod and Wegge, 1995). Understanding the forest use strategies and dependence of forest dwellers (Kazungu et al., 2020), and considering the impact of illegal logging (Khai et al., 2020b) are important in developing effective management strategies for tropical production forests.

In Myanmar, about 42.9% of the country area is covered by the forests, defined as land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use (Food and Agriculture Organization—FAO, 2014). Of which about 73.0% of the country's forest area are managed as PFE, and the remained forested area about 27.0% are called unclassified forests, enforced by the Myanmar Forest Law (Forest Department, 1992). The PFE is classified into production forests (59.4% of the country's forest area), and protected area (PA) (13.6% of the country's forest area). The policy target and the commitment to UNFCCC intended to constitute PFE from 30% in 2019 up to 40% of total country area by 2030. Timber harvesting in production forests has been conducted since 1856 using Myanmar Selection System (MSS), which is said as an environmentally friendly and relatively low impact logging practice (Brunner et al., 1998).

On the other hand, the national-scale field surveys conducted in 2013 revealed that the production forests in Myanmar have been settled by local people without permission in approximately 700,000 ha covering a total of ca. 300,000 households in ca. 4000 villages. Moreover, remote sensing studies (Mon et al., 2012, 2010), large-scale forest inventory study (Win et al., 2018b) confirmed the occurrence of widespread large-scale forest degradation, which was defined as reduction of canopy cover, in selectively logged forests due to over-harvesting and illegal logging following logging operations (Khai et al., 2016; Win et al., 2018d).

Making efforts in reducing and restoring the degraded forests, the government launched a logging ban for 2016–2017 over the country and for 10 years in the Bago Yoma region. Also, Myanmar Reforestation and Rehabilitation Program (MRRP) was started in 2017 for 10 years to restore degraded forest within the Permanent Forest Estate. However, there are limited empirical knowledge on forest use strategies and dependency of local people in production forests, effectiveness of logging ban, and stand dynamics in selectively logged production forests. A few studies observed illegal logging in production forests (Khai et al., 2016; Win et al., 2018d), and local people's dependency on production forests (Khaine et al., 2014a; Soe and Yeo-Chang, 2019) in Myanmar. However such studies made one time data analysis, and couldn't catch the changes over time.

1.2. Research objectives

The main objective of in this study is to observe changes of people's dependency, in terms of dependence level for cash income and forest use strategies, on selectively logged forests over time, and impacts of illegal logging on stand dynamics in selectively logged production forests using the time series data. Then, I discuss what the problems are in production forests and how to improve the management of production forests.

Specific objectives are;

1) To detect forest use strategy and dependence level of people living outside and inside the selectively logged production forests
2) To evaluate dynamic of forest use strategy and dependence level in responding logging ban practice
3) To observe the condition of illegally logged stand in production forests
4) To observe stand dynamics and interactions among adult-trees, bamboos, and tree regeneration in illegally logged production forests

1.3. Structure of dissertation

The dissertation comprises six chapters in total as follows (Figure 1.1);

Chapter 1 represents introduction on the background and objectives of this study.

Chapter 2 detected the forest use strategies and dependence level of people living outside and inside the production forests, and explored the determinants as well.

Chapter 3 revealed the changes of forest use strategies and dependence level of people living adjacent to the production forests after the logging ban.

Chapter 4 observed the intensity of illegal logging and condition of remaining stands in post-logged forests, where people settled illegally.

Chapter 5 studied stand dynamic of the illegally logged production forests over 5 years and interaction among adult-tree, bamboo, and regenerated tree.

Chapter 6 highlighted general conclusion upon the research findings and provided recommendations to be effective management.

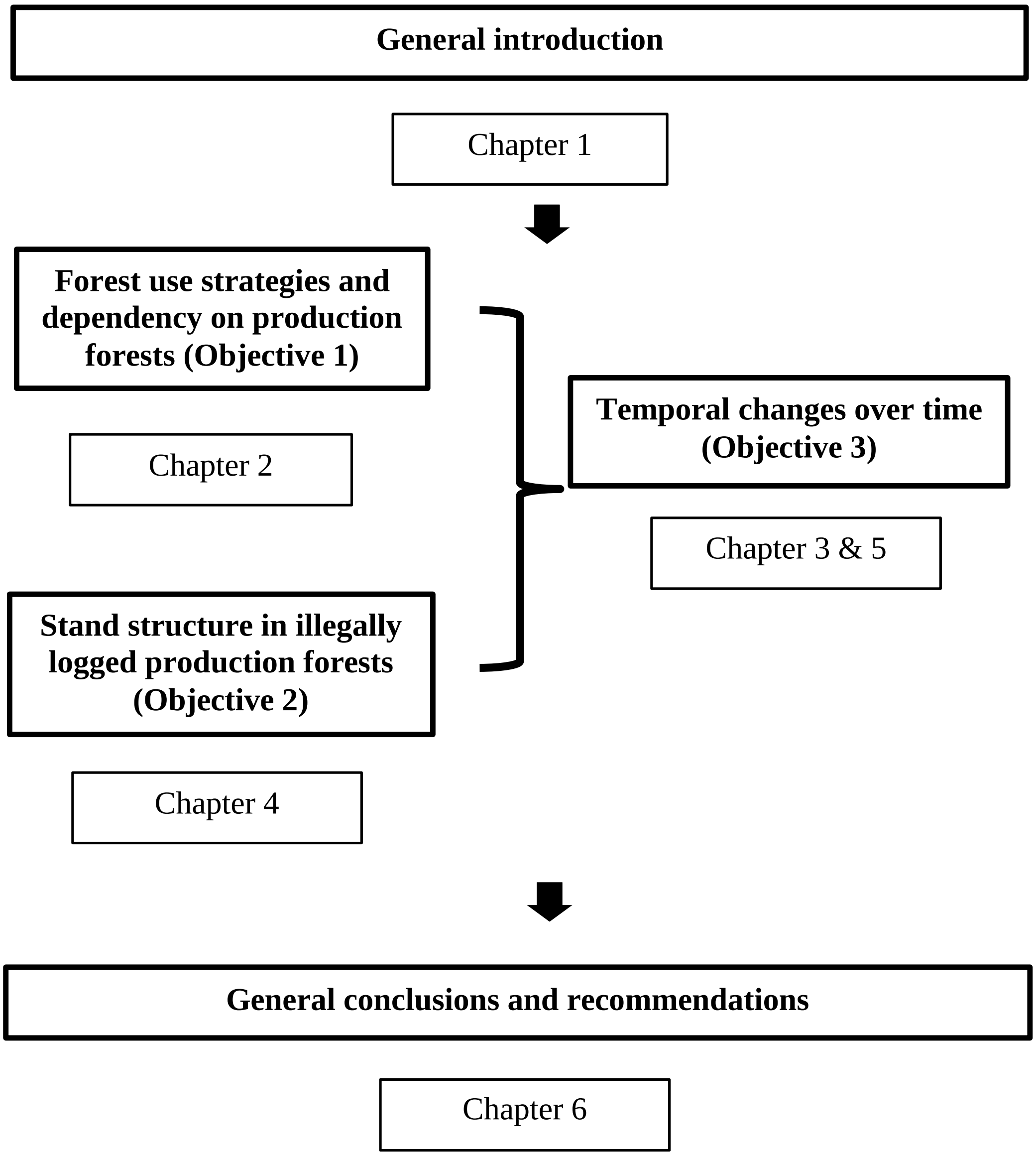

Figure 1.1. Framework of dissertation.

Chapter 2

Differences in forest use strategies for cash income between households living outside and inside selectively logged production forests in Myanmar

2.1. Introduction

Global attention has focused on deforestation and forest degradation in tropics, which can reduce various ecosystem services (e.g. Foley et al., 2007). Designation of a permanent forest estate (PFE) within a legal framework is a commonly used practice to combat deforestation and forest degradation in natural tropical forests (Food and Agriculture Organization—FAO, 2016). Under PFEs, there are different zones, such as protected areas and production forests, where the forest use activities by local people are restricted. One of the important aspects for sustainable management of PFEs is the forest dependency of local people living adjacent to PFEs; this is because 1.6 billion people around the globe substantially depend on forests for their livelihoods (World bank, 2004). Understanding the dependency and conservation attitudes of local people toward the forests surrounding them is of great importance to formulate new or modify existing conservation strategies (Garekae and Thakadu, 2017).

Many studies in tropics have investigated the forest dependency of local people and found that forest income makes a significant contribution to rural livelihoods (Fikir et al., 2016; Kamanga et al., 2009; Mukul et al., 2015). Vedeld et al. (2007) summarized 51 case studies from 17 countries covering Asia, Africa, and Latin America, revealing that forest environmental income made up 22% of the total income on average. A similar share was confirmed by Angelsen et al. (2014), who used data from 7978 households in 29 tropical countries. Forest income usually includes cash income and subsistence income from products harvested in forested areas such as firewood, timber, and non-timber forest products (NTFPs) (e.g. Angelsen et al., 2014; Vedeld et al., 2007). Despite the growing literature on forest dependency, however, there is still a limited understanding of diversity in forest use strategies among local people. This was pointed out by Kazungu et al. (2020), who classified forest use strategies into three groups: specialized charcoal sellers, forest food and charcoal sellers, and pure subsistence forest users. Additionally, previous studies on forest income dependency are often biased toward sites around protected areas, such as national parks and forest reserves (e.g. Aung et al., 2015; Garekae and Thakadu, 2017), and fewer studies focus on income dependency around production forests. A few studies have reported impacts from selective logging in natural tropical production forests on NTFPs of livelihood importance, but most studies focus on the ecological aspects of conflicts and compatibility in species for timber and NTFPs (e.g. Rist et al., 2012).

Myanmar is one of the biodiversity hotspots in the Indo-Pacific region (Htun et al., 2012) and forest still covers around 42.9% of the country. The forestry sector is one of the main contributors to the national economy, while forests play a vital role in local livelihoods, because around 68% of the total population are rural people living near forests (Department of Population, 2015). In Myanmar, all of the forest areas are state-owned, and the 73.0% of the country's forest area are managed as PFE, enforced by the Myanmar Forest Law (Forest Department, 1992). The remainder of the forests are called unclassified forests (27.0%). The PFE is classified into production forests (59.4% of the country's forest area), which include reserved forest (RF), protected public forest (PPF), and protected area (PA) (13.6% of the country's forest area). The RF is designated for timber export from higher-value commercial species while the PPF is mainly for local use of lower commercial value species. Legal timber extraction is mainly carried out in RF and PPF, but local community access for commercial purposes is strictly prohibited (Forest Department, 1992).

Myanmar has practiced selective logging for timber production in natural forests since 1856 under the Myanmar Selection System (MSS), which still uses elephants for skidding. However, recent studies by remote sensing and field surveys revealed large scale forest degradation, mainly caused by over-harvesting from illegal logging (Mon et al., 2012; Win et al., 2018d). In 2013, the Myanmar government conducted national-scale field surveys in the RF and PPF, indicating that approximately 700,000 ha within RF and PPF were encroached upon by local people. The encroachment areas were illegally used as residential, agricultural, and religious lands by a total of ca. 300,000 households in ca. 4000 villages. Dealing with encroachment in production forests is one of the most important political and administrative issues. The Myanmar forest law prohibits the commercial use of the RF and PPF without permission while the subsistence use is allowed. However, forest use strategies for cash income are still not well understood for local households living in the encroachment areas within the production forests in Myanmar or even for households adjacent to the production forests. Therefore, this study aimed to clarify the differences in forest use strategies for commercial purposes and forest cash income dependency between local people living outside and inside RFs in Myanmar, then to discuss the forest management implications.

2.2. Materials and Methods

2.2.1. Study area

My study site is located in Bago Township, which is part of southeastern Bago Yoma in Myanmar, between latitudes 17°14′ N and 17°50′ N and longitudes 96°24′ E and 94°41′ E (Figure 2.1). The average annual rainfall and temperature are approximately 3360 mm and 27 ℃, respectively (Bago Forest Department, 2006). Bago Yoma is known as the home of the teak bearing forests with relatively abundant valuable commercial timber species in Myanmar, and it has been one of the country's major timber-producing areas (Mon et al., 2012). Bago Township covers an area of 2905 km^2, of which around 53% is occupied by forests. The dominant forest type is a moist upper mixed deciduous forest, which is known for its abundance of teak (*Tectona grandis*), pyinkado (*Xylia xylocarpa*), and other commercial species. The forested areas have been designated as eight RFs that are protected by Forest Law; nobody has the right to enter into these areas or to harvest any forest products for commercial purposes without permission (Figure 2.1). Official timber harvesting for the national economy has been practiced in all of these RFs using the Myanmar Selection System since 1856.

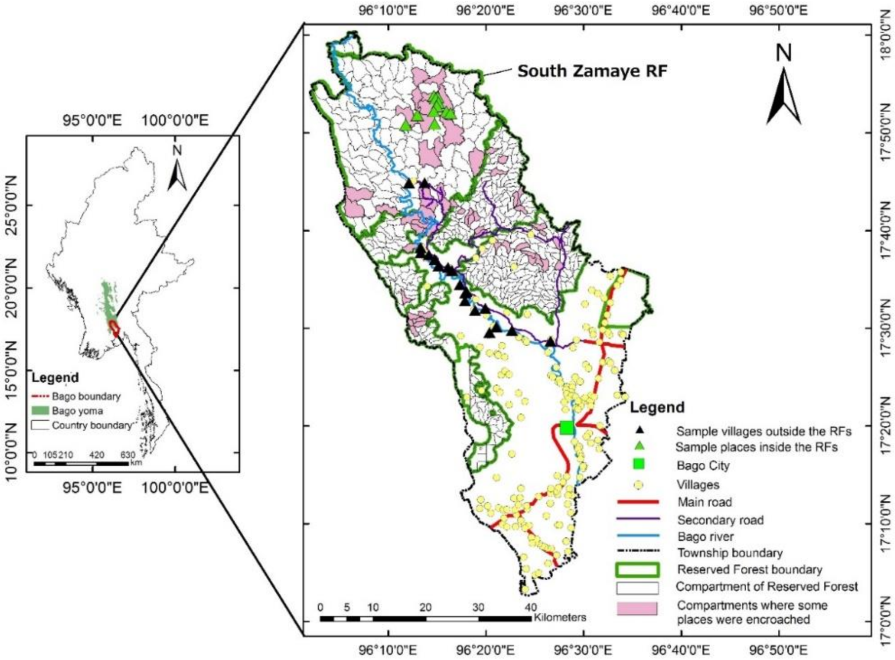

Figure 2.1. Study sites at Bago Township, Myanmar.

In 2013, when I conducted the field surveys, there were 491,434 people and 107,132 households in Bago Township, and 48.2% of people lived in rural areas. The overall mean household size in the Township is 4.4 members per household [11]. The Township comprises one big city called Bago and 229 villages (Figure 2.1). Approximately 807 households were temporarily living within the compartments of the RF areas without permission, which was regarded as encroachment (Forest Department, Bago Township, 2013). Of the total of 229 officially registered villages, two were located within the boundaries of the RFs, but because these villages were officially approved and registered, I regarded them as "outside" the RFs, rather than as part of the encroachment (Figure 2.1).

2.2.2. Data collection

Data collection was conducted for households living outside and inside the RFs using a questionnaire survey in March and December 2013. Information was collected mainly through a meeting with the head of each household using a structured interview. The field survey team for the household interview consisted of both male and female undergraduate students with accompanying representatives from each selected village or community. Before starting an interview, the respondents were informed that the interview was only for academic research and did not concern any authority. The survey questionnaire was written in the national language to allow a clear understanding. It mainly focused on the knowledge of the household heads about the nearby RF, socio-economic conditions, resource use patterns, and livelihoods.

2.2.2.1. Household surveys outside the RFs

Out of the 229 villages which are registered as administrative villages, a total of 19 sample villages were selected for this study along the seasonal secondary road and the river to cover different levels of accessibility to the forest (Figure 2.1). All the sample villages were situated on the secondary road, which was constructed mainly for use in official timber harvesting operations. This road is used for transportation by local communities in summer (February–May) and winter (October–January) seasons. In the rainy season (June–September), local communities in the sampled villages use the Bago river, which runs from north to south across Bago Township, for transportation. Therefore, most of these sampled villages had poor access to the city and markets for their products. As a consequence, most residents from these villages had relatively low education levels and poor socio-economic conditions. All the villages had been situated around the RFs for over 80 years. Local communities had legal right to the forest only for their basic needs, and commercial use without permission was prohibited by Forest Law 1992 (Forest Department, 1992). The total population and number of households in the 19 sampled villages were 30,194 and 5679, respectively. The average land holdings per household among the 19 villages were approximately 1.60 ha.

Among the 5679 households living in the 19 sampled villages, 146 households were randomly selected with a sampling intensity of 2.6% of the total households. They mainly depended on agriculture and forest for their livelihood because of the poor accessibility to city, market and off-farm opportunities. First, a group discussion with 10 to 15 members was conducted, including the key informants from relevant villages, the head of the village, and the village elders who knew about the village to get advices on the sampling intensity, depending on the heterogeneity or homogeneity of the livelihoods of the respective villages. Next, practice household surveys were carried out to test the questions. Then, 7–14 households from each selected village were randomly chosen. Informal discussions were also carried out with the village heads, the village elders, and the respondents who voluntarily participated in the discussions, to gather more information to assist with the interpretation of the responses.

2.2.2.2. Household surveys inside the RFs

Although the RFs are protected by Forest Law and nobody can settle in them without permission (Forest Department, 1992), around 807 households (hereafter, called encroachers) were living without permission within fifty eight compartments of the RFs in 2013 (FD Bago, 2013, Figure 2.1). Approximately 41% (334 encroachers) of total encroachers were living in the South Zamaye RF in 2013, where legal logging operations were being conducting. They were moving from one place to another within the forests using the logging road constructed in the legal logging operation.

The questionnaire survey was conducted in December 2013 with the encroachers living in the South Zamaye RF. Of the 119 compartments in South Zamaye RF, 20 compartments were encroached upon by local communities (Figure 2.1). Six out of the 20 compartments were selected subjectively considering accessibility and proximity to the current timber production site (Figure 2.1). Approximately 14% (48 households) of total encroacher households in South Zamaye RF were chosen randomly for the survey. Then, the survey was conducted using a pre-structured questionnaire related to encroachers' livelihoods, encroachment patterns, and dependency on forests. Unlike the survey for the outside households, group discussion with the key informants was not conducted for the inside households.

2.2.3. Data analysis

I classified household cash income into forest cash income and non-forest cash income based on income sources. I defined forest cash income as cash income from activities within the RFs, such as collecting and/or producing forest products by households within the RFs, and labor, farming and small shops within the RFs. Non-forest cash income was defined as earnings from activities outside the RFs such as agriculture and small business. Some households earned only forest cash income or only non-forest cash income while others earned from the combination of forest cash income and non-forest cash income. In this study I found a total of 13 different cash income strategies, as listed in Table 2.1.

Table 2.1. Cash income sources and household cash income strategies found in this study.

Cash income sources	Household cash income strategies	Households living outside the RFs (n = 146)		Households living inside the RFs (n = 48)	
		n	%	n	%
Only forest cash income	Only charcoal production	3	2.1	20	41.7
	Charcoal production and opening shop in RF			1	2.1
	Charcoal production and bamboo cutting	16	2.1		
	Only bamboo cutting	4	2.7		
	Only labor in RF	1	0.7	1	2.1
Only non-forest cash income	Only agriculture	28	19.2		
	Only business (opening shop in villages and small-scale animal husbandry)	13	8.9		
	Other non-forest activities (labor in villages, combination of agriculture and business or labor in villages)	30	20.5		
Combination of forest and non-forest cash income	Charcoal production and non-forest activities	5	3.4	24	50.0
	Charcoal production, bamboo cutting and non-forest activities	9	6.2	2	4.2
	Bamboo cutting and non-forest activities	31	21.2		
	Farming in RF and non-forest activities	4	2.7		
	Labor in RF and non-forest activities	2	1.4		
Total		146	100	48	100

Non-forest activities include agriculture, small business (including livestock raising), and labor outside the reserved forests (RFs).

Forest cash income dependency was calculated as the ratio of forest cash income against the total annual household cash income (Adam and Tayeb E L, 2014). The total household cash income was calculated as the sum of forest cash income and non-forest cash income. Some households earned cash income from the combination of forest cash income and non-forest cash income (Table 2.1). Therefore, I divided such combined household cash income into forest cash income and non-forest cash income, when I evaluated forest cash income dependency, which was calculated as forest cash income divided by total (forest and non-forest) cash income. I also classified total household income of each household into 5 forest cash income and 3 non-forest cash income sources as shown in Table 2.1, then I calculated the averages for the outside- and inside-households.

The products consumed directly by the household or given away to friends and relatives were assumed as subsistence and the value of these products was not counted in calculating household annual cash income. The income in Myanmar Kyat (MMK) was changed to US dollars using the exchange rate (1 USD = 800 MMK) at the time of data collection. Cash income from forest-based products and agriculture was calculated based on the productivity and the price received in their sale, and the cost for all purchased inputs (such as purchased fertilizer or hired labor) was deducted to arrive at the net income. Livestock income included only income from the sale of animals within a year.

Descriptive statistics were used to explore the main characteristics of respondents concerning their socio-economic status, knowledge about the RFs, and dependency on the forests. I compared the overall mean of a continuous variable between households living outside and inside the forest using Wilcoxon rank sum *t*-test statistic (Table 2.2). I used chi-squared test for differences in categorical variables (Table 2.3). I also used chi-squared test to confirm differences in cash income strategies between the outside- and inside-households in term of the household number (Table 2.1) and of income distribution among different income strategies (USD/year).

Table 2.2. Continuous variables of socio-economic characteristics for the sample households.

Continuous Variables	**Unit**	**Households Living Outside the RFs**	**Households Living Inside the RFs**	**Wilcoxon Rank Sum Test**
		***n* = 146** Mean ± SD	***n* = 48** Mean ± SD	
Age of head	Years	47.1 ± 10.5	33.7 ± 9.9	$p < 0.0001$
Family size	Persons	5.4 ± 1.8	4.6 ± 1.8	$p = 0.013$
Farmland area	Hectare	2.3 ± 2.7	0.53 ± 1.2	$p < 0.0001$
Total cash income	USD/year	1701 ± 1083	1090 ± 547	$p < 0.0001$
Forest cash income dependency	%	32 ± 38	83 ± 19	$p < 0.0001$
Duration of residence	Years	38.2 ± 16.0	6.3 ± 6.2	$p < 0.0001$

Table 2.3. Categorical variables of socio-economic characteristics for the sample households.

Categorical variables	Definition	Classes	Households living outside the RFs (n = 146) %	Households living inside the RFs (n = 48) %	Chi-squared test
Education	Education level of the household head	Primary (grade 1–4)	75	81	$\chi^2 = 1.1297$ p = 0.5684
		Middle (grade 5–8)	17	15	
		High (grade 9–)	8	4	
Accessibility to forest	The time to the RFs to collect forest products	Bad (more than 1 day)	22	0	$\chi^2 = 11.058$ p = 0.0009
		Good (within 1 day)	78	100	
House possession	Household own a house for permanent settlement	Own	99	73	$\chi^2 = 0.034723$ p = 0.8522
		Not own	1	27	
Knowledge about the law of RFs	Household head's knowledge about the prohibited access to RFs by Forest Law	Known	67	79	$\chi^2 = 1.9583$ p =0.1617
		Unknown	33	21	
Knowledge about the boundary of RFs	Household head's knowledge about the boundary of RFs	Known	54	79	$\chi^2 = 8.4571$ p = 0.0036
		Unknown	46	21	

Moreover, linear regression models were developed to explore the factors influencing forest cash income dependency. Forest cash income dependency was used as the dependent variable. I used five continuous variables and five categorical variables, shown in Tables 2.2 and 2.3, as independent variables, based on the previous studies on forest dependency. These were related to socio-economic conditions and knowledge of the forest-dependent communities, and the hypothesized effects were shown in the Supplementary Material Table S1. Before running the model, I checked for multi-collinearity among independent variables and confirmed no collinearity using a Variance Inflation Factor (VIF) < 5 (Lonn et al., 2018). In this study, I built three regression models for (1) all the sample households living outside and inside the RFs (n = 194), (2) households living outside the RFs (n = 146) and (3) households inside the RFs (n = 48). In the model for the inside households, the variable "accessibility to forest" was not used because all the sample had the same value "Good" (Table 2.3), and the variable "Knowledge about the boundary of the RFs" was not used because the value for each household (known or unknown) was identical to that of the variable "Knowledge about the law of the RFs" (Table 2.3). All statistical analyses were conducted using the R environment (R Core Team, 2019).

2.3. Results

2.3.1. Socio-economic characteristics of households

All the continuous variables were significantly different between households outside and inside the RFs (Table 2.2). The outside-households had a much higher total income (mean ± SD; 1701 ± 1083 USD/year) than the inside-households (1090 ± 547 USD/year), while forest income dependency was much higher for the inside-households (83 ± 19%) than the outside-households (32 ± 38%). The outside-households tend to have older household heads, larger family sizes and farmland area, and longer duration of residence (Table 2.2).

Among the categorical variables shown in Table 2.3, relatively large differences between the outside- and inside-households were found in relation to accessibility to forest, house possession, and knowledge about the boundary of RFs. Approximately half (47%) of the outside-households did not know the boundary of RFs while most (79%) of the inside-households knew it. In contrast, many households both outside and inside the RFs knew the law of RFs (Table 2.3).

2.3.2. Household cash income strategies

Clear differences in cash income strategies were found between the outside- and inside-households (chi-squared = 16.7, df = 12, $p < 0.0001$; Figure 2.2, Table 2.1). For the outside-households, almost half (49%) of the households got cash income only from activities that were not related to forests, such as agriculture and business, whereas the other half earned some cash income from forest-related activities (charcoal production, bamboo cutting, labor, and shop in RFs) (Figure 2.2, Table 2.1). In contrast, all the inside-households got cash income from forest-related activities. Around 46% the inside-households' cash income was only from forest-related activities, whereas the income strategies for the other 54% were combinations of forest-related and non-forest activities (Figure 2.2, Table 2.1).

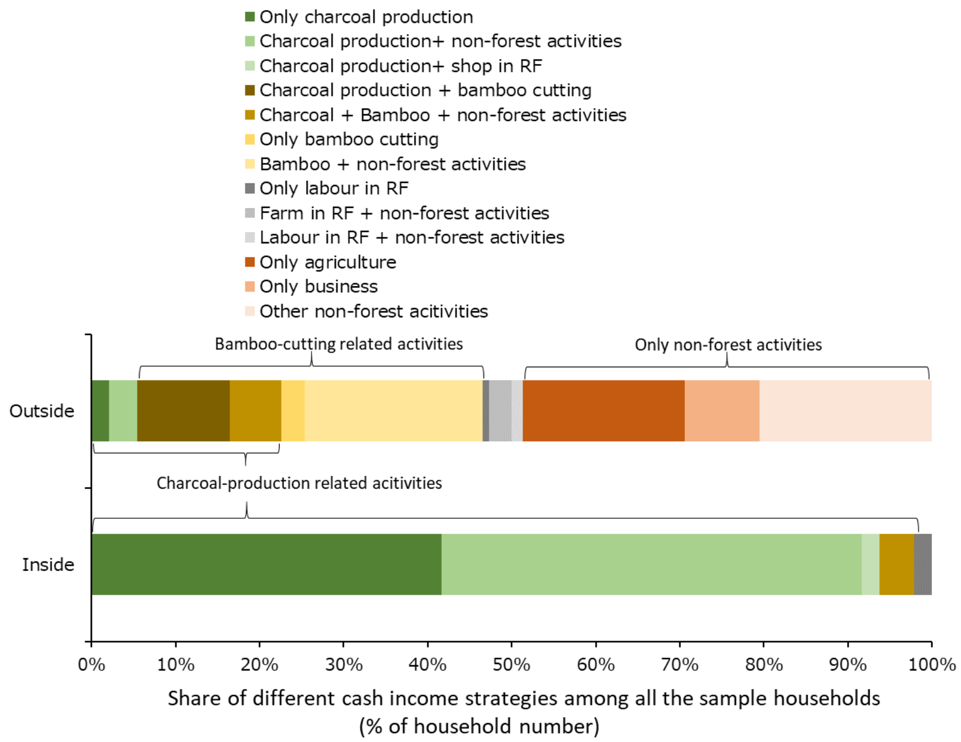

Figure 2.2. Share of different cash income strategies among all the sample households (% of outside- and inside-households).

Forest use strategies for cash income were also quite different (Figure 2.2, Table 2.1). For the outside-households, bamboo-cutting activities were more common (41% of the sample households) than charcoal-production activities (23%). In contrast, the majority of the inside-households (98%) were engaged in charcoal production while only 4% of households carried out bamboo cutting.

Among the 12 different cash income strategies found in outside-households, the average cash income was highest for the combination of labor in RF and non-forest activities (3125 USD), followed by the combination of charcoal production, bamboo cutting and non-forest activities (2556 USD), then only business (2462 USD) (Figure 2.3). Among the five cash income strategies of the inside-households, the combination of the charcoal production and shop in RF was highest (2375 USD), but the other four strategies were not significantly different (ANOVA, $p > 0.05$) and the incomes of the inside-households from these four strategies were significantly lower than those of the outside-households (Figure 2.3).

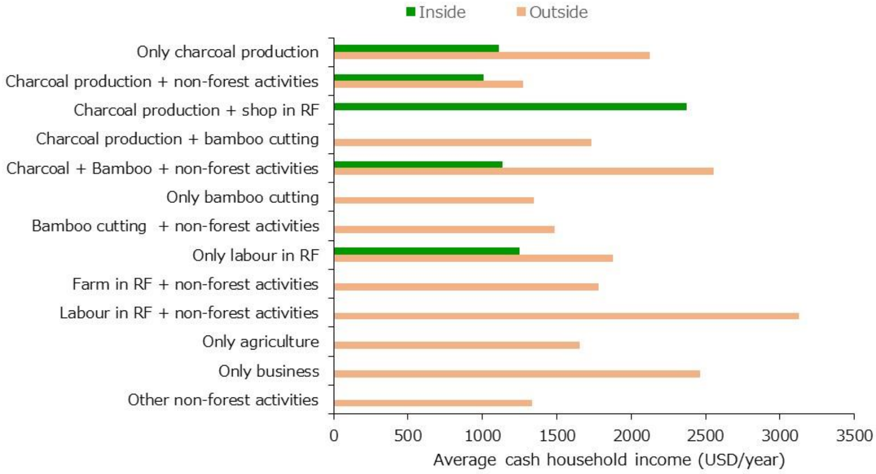

Figure 2.3. Average household cash income (USD/year) for each of cash income strategies.

2.3.3. Forest cash income dependency

Average total cash income was classified into 5 forest cash income and 3 cash non-forest income sources (Figure 2.4). These cash income distribution patterns among eight different income sources were significantly different between the outside- and inside-households (chi-squared = 1765.4, df = 7, $p < 0.0001$; Figure 2.4). Of the average cash income for all the inside-households (1090 USD), 800 USD (73%) were earned from only charcoal production, while cash income from non-forest activities was only 13% of the total cash income (Figure 2.4). For the outside-households, the cash income only from charcoal production was only 4% (65.5 USD) of the total average income (1701 USD), and a higher proportion of cash income was found in only bamboo cutting (10%) and the combination of charcoal production and bamboo cutting (17%) (Figure 2.4).

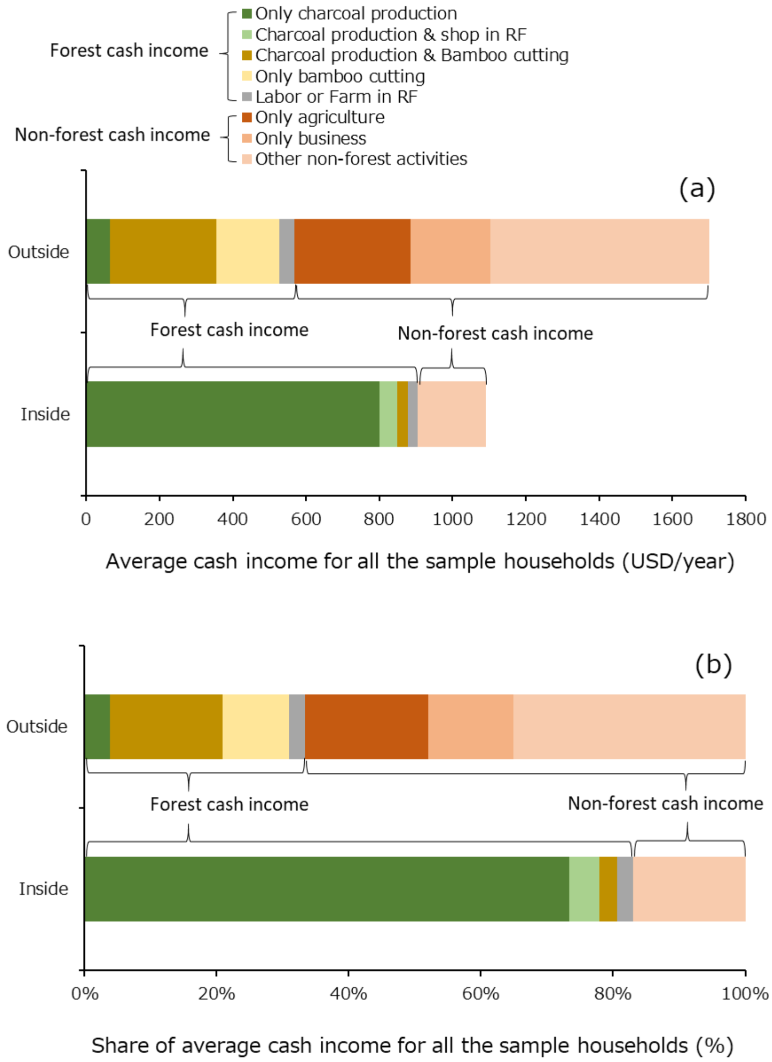

Figure 2.4. Average total cash income for all the sample households with being classified into 5 forest cash income and 3 non-forest cash income sources. The units are (**a**) USD/year and (**b**) share (%) of average income.

2.3.4. Factors affecting forest income dependency

There were similar regression results using all the outside- and inside-households (n = 194) and only the outside-households (n = 146), while these results were different from those using only the inside-households (n = 48). For the outside-households, farmland area and duration of residence negatively affected forest dependency, while accessibility to forest and knowledge on forest law positively affected it (Table 2.4). This indicates that more farmland and longer duration of residence lowered the dependency level, and the dependency was higher for households with better access to forest and the household head's recognition of the prohibition relating to RFs under Forest Law. For the inside-households, the regression model cannot significantly explain the variation of forest dependency (p = 0.4859) even though family size may negatively influence the dependency (Table 2.4).

Table 2.4. Parameter estimates of the linear regression models explaining forest cash income dependency (%).

Coefficients	Households living outside and inside the RFs (n=194)				Households living outside the RFs (n=146)				Households living inside the RFs (n=48)			
	Estimate	Std. Error	*t* value	Pr (>|t|)	Estimate	Std. Error	*t* value	Pr (>|t|)	Estimate	Std. Error	*t* value	Pr (>|t|)
(Constant)	6.093×10^{-1}	1.623×10^{-1}	3.753	<0.001	3.553×10^{-1}	3.245×10^{-1}	1.0950	0.2756	8.319×10^{-1}	2.047×10^{-1}	4.064	<0.001
Age of head (Years)	-1.594×10^{-3}	2.659×10^{-3}	-0.599	0.550	-1.358×10^{-3}	3.346×10^{-3}	-0.4060	0.6855	-8.762×10^{-5}	3.402×10^{-3}	-0.026	0.980
Family size (Persons)	-1.464×10^{-2}	1.407×10^{-2}	-1.040	0.300	-5.103×10^{-3}	1.780×10^{-2}	-0.2870	0.7747	-4.481×10^{-2}	1.760×10^{-2}	-2.547	0.015
Farmland area (hectare)	-3.619×10^{-2}	1.081×10^{-2}	-3.349	0.001	-3.907×10^{-2}	1.219×10^{-2}	-3.2050	0.0017	2.617×10^{-2}	2.645×10^{-2}	0.990	0.329
Total cash income (USD/year)	1.873×10^{-5}	2.407×10^{-5}	0.778	0.438	2.963×10^{-5}	2.715×10^{-5}	1.0910	0.2770	-4.879×10^{-6}	5.893×10^{-5}	-0.083	0.934
Duration of residence (Years)	-7.222×10^{-3}	1.599×10^{-3}	-4.517	<0.001	-4.336×10^{-3}	2.074×10^{-3}	-2.0910	0.0384	2.152×10^{-4}	5.672×10^{-3}	0.038	0.970
Education (Middle)	1.081×10^{-1}	1.062×10^{-1}	1.017	0.310	1.061×10^{-1}	1.250×10^{-1}	0.8490	0.3973	3.374×10^{-2}	1.599×10^{-1}	0.211	0.834
Education (Primary)	1.697×10^{-1}	9.660×10^{-2}	1.757	0.081	1.462×10^{-1}	1.140×10^{-1}	1.2830	0.2019	1.254×10^{-1}	1.482×10^{-1}	0.846	0.403
Accessibility to forest (Good)	1.604×10^{-1}	6.439×10^{-2}	2.491	0.014	1.323×10^{-1}	6.989×10^{-2}	1.8930	0.0606	NA	NA	NA	NA
House possession (Yes)	-1.228×10^{-1}	9.049×10^{-2}	-1.357	0.176	-4.265×10^{-2}	2.535×10^{-1}	-0.1680	0.8667	3.226×10^{-2}	6.769×10^{-2}	0.4770	0.6364
Knowledge about the law of RFs (Known)	1.639×10^{-1}	6.982×10^{-2}	2.348	0.020	1.817×10^{-1}	7.762×10^{-2}	2.3410	0.0207	8.099×10^{-2}	7.272×10^{-2}	1.1140	0.2723
Knowledge about the boundary of RFs (Known)	-6.806×10^{-2}	6.452×10^{-2}	-1.055	0.293	-8.418×10^{-2}	7.126×10^{-2}	-1.1810	0.2396	NA	NA	NA	NA
	R^2 = 0.4143				R^2 = 0.2446				R^2 = 0.1855			
	Adjusted R^2 = 0.3789				Adjusted R^2 = 0.1826				Adjusted R^2 = -0.007404			
	F value = 11.7				F value = 3.944				F value = 0.9616			
	p value < 0.00001				p value < 0.00001				p value = 0.4859			

Note; NA indicates that this variable was not used for regression because "Accessibility to forest" was "Good" consistently and "Knowledge" was identical between "law" and "boundary" for all the households living inside the RFs (n=48).

2.4. Discussion

2.4.1. Forest use strategies for cash income

In this study, I found large differences in cash income strategies between households living outside and inside the RFs. All the inside-households were engaged in forest-related activities for cash income generation, whereas only half of outside-households earned cash income from forest-related activities. The other half of outside-households' cash income was from non-forest activities such as agriculture, small business including livestock raising, and labor outside the RFs (Figure 2.2). In this study site, all the farming was rain-fed and, therefore, farmers practiced farming only in specific months. During the rest of the year, many households collected forest products to earn extra income, which is common livelihood practice in rural regions (Byron and Arnold, 1999). The encroachers (the inside-households) had significantly smaller areas of farmland (0.53 ha) than the outside-households (2.33 ha), and only 73% of encroachers possessed a house in their respective villages (Table 2.2). Nearly all the encroachers earned their forest-related income from charcoal production (Figure 2.2). Therefore, the encroachment in this study was unlikely to be for permanent settlement and farming. The encroachers had significant lower average annual cash income (1090 USD) than that of the outside-households (1701 USD). This arises from lower average cash income for four of their income strategies: only charcoal production, charcoal production + non-forest activities, charcoal + bamboo + non-forest activities, and only labor in RF (Figure 2.3). This lower cash income may be because encroachers had smaller family sizes or had smaller farm sizes, or both (Table 2.2).

2.4.2. Forest cash income dependency

Local communities living around the RFs have access to them only for subsistence and have been prohibited from using RFs for commercial purposes by the Forest Law in Myanmar. However, substantial forest cash income dependency was found not only for the inside-households (83%), but also for outside-households (32%). This is within the values reported in previous studies. For example, forest income dependency was reported in protected areas in Myanmar: 38.8% for three villages surrounding the Popa Mountain Park by Htun et al. (2017) and around 50% for two villages around Natma Taung National Park by Aung et al. (2015). The forest dependency values in villages near the production forests in Bago Yoma region, Myanmar, which is the same region as this present study, were also reported to be 25% in 10 villages in both western and eastern aspects of Bago Yoma region by Khaine et al. (2014), and 37% in the Taungoo District by Soe and Yeo-Chang (2019). The reported values for forest income dependency for other countries included 21% in Ethiopia (Fikir et al., 2016), 12% in Malawi (Kamanga et al., 2009), and 47% in Pakistan (Hussain et al., 2019).

The encroachers' dependence level for cash income (83%) was much higher than that of the outside-households (32%). This result is probably because most encroachers practiced year-round charcoal production as their main forest use activity (Figure 2.2) while many outside-households combined seasonal bamboo cutting with farming or small business. The finding that charcoal making and bamboo cutting were the main forest use activities in this study was consistent with that of (Soe and Yeo-Chang, 2019) who conducted household surveys near the production forest in the Taungoo district, Bago Yoma region in Myanmar. Khaine et al. (2014) also reported that bamboo and bamboo shoots were the most collected NTFPs in the Bago Yoma region, Myanmar.

2.4.3. Factors affecting forest cash income dependency

I found large differences in factors affecting forest cash income dependency between the outside- and inside-households. For the outside-households, farmland size had a negative correlation with the dependency level (Table 2.4). This is compatible with the hypothesized effect, indicating that more income generated from agriculture can lower forest dependency (Table S1). Studies have highlighted that limited access to agricultural land creates more dependency on the forest (Jain and Sajjad, 2015; Kamanga et al., 2009). Similarly, a lack of land availability can drive local people to encroach into forested areas (Iftekhar and Hoque, 2005; Mon et al., 2012). The duration of residence was found to have a negative relation with the forest cash income dependency. This is also along with the hypothesis that the households living longer in a village may have more secure usufruct rights to their land and they may be less dependent on forest products (Tables 2.4 and S1). Regarding knowledge of forest law, it was hypothesized to have a negative correlation, whereby people who knew about the prohibition on commercial forest use in RF would have lower forest dependency (Table S1). However, there was actually a positive relationship with the dependency level (Table 2.4); even though respondents knew about the prohibition, they were dependent on the forest for their livelihood. Forest Department staff made announcements to stop illegal activities and move encroachers out from the forest, but after a few months of conducting such law enforcement activities, encroachers began illegal activities again. This confirmed the finding of other studies, which showed that law enforcement and limiting access to forest resources cannot solve the problem of illegal activities (Studsrod J. E & Wegge, 1995). According to Forest Law in Myanmar, access to forest resources for subsistence purpose is permitted, but villagers still need to earn a cash income. Having a positive association between accessibility to forest and dependency level is consistent to the finding in Cameroon that easy access to forest resources created more dependency on the forest (Mukete et al., 2018).

For the inside-households, the regression model failed to explain the variation of forest cash income dependency (Table 2.4). This may be because the sample size and variation of the dependent variable were relatively small for the inside-households (Table 2, n = 48, mean ± SD = 83 ± 19%).

2.4.4. Forest management implications

One of the critical issues in Myanmar forestry is that there has been widespread forest degradation in selectively logged production forests (Mon et al., 2012; Win et al., 2018b). Ecological field-surveys revealed that illegal logging occurred after legal logging operations (Win et al., 2018b, 2018d). Illegal logging most likely targeted first larger trees of commercially valuable timber species such as teak (*Tectona grandis*) and pyinkado (*Xylia xylocarpa*), and after depletion of these timber trees, trees of various species and sizes were illegally cut for charcoal making (Khai et al., 2016). The socioeconomic field-surveys of this present study confirmed that illegal charcoal production was widely conducted in RFs and such charcoal production was the major income strategy for the encroachers. Because charcoal demand is likely to grow in rural areas of Myanmar, there may be an increasing risk of further forest degradation because of charcoal making (Win et al., 2018c). To deal with this matter, more community forestry programs should be implemented to achieve sustainable production of charcoal in rural regions.

This study also found that bamboo collected in RFs was one of the important cash income strategies for households living near the RFs. Bamboos are often dominant in degraded forests in tropical mixed deciduous production forests in Myanmar, and bamboo-dominated conditions can hamper tree regeneration (Khai et al., 2016). Thus, promoting bamboo cutting by local households may contribute not only to their income generation but also to the restoration of degraded forests. Providing legal rights to access the RFs for bamboo cutting would be an incentive for local households to facilitate sustainable production of bamboos as well as other NTFPs.

2.4.5. Study limitations

In this study, the data collected in December 2013 were used for the analysis. Thus, the household cash income strategies and forest cash income dependency might have changed under changing the condition of forest management strategy and rural development in the past seven years. Regarding forest management strategy, a logging ban was introduced in 2016 for one year in the whole country and for 10 years in the Bago Yoma region, including my study site. Accessibility to the forest was highlighted as an influencing factor on forest cash income dependency. Because all the sample households were situated on the secondary roads, which were constructed mainly for use in legal logging operations, the logging ban may affect the changes of household income strategies and income dependency. Providing legal rights to access the RFs for income generation is still limited for local households. Community forestry has been practiced since 1995 in Myanmar mainly to meet the basic needs of local people. The revised community forestry instruction in 2019 aimed not only to provide basic needs but also to enhance and employment income opportunities of local communities. However, the effectiveness of changes in forest policy on the livelihoods of local communities is still unknown. Therefore, this study calls for further study to assess the changes of income strategies and forest income dependency after seven years using the baseline information of this study to formulate more effective policy measures.

2.5. Conclusions

This study revealed that the selectively logged production forests (RFs) in Myanmar were largely used for income generation by households living both outside and inside the RFs, even though most households knew that the forest law prohibited access to RFs for commercial purposes without permission. The inside-households (encroachers) were more dependent on the forest for cash income than the outside-households. The main forest use activity of the encroachers was charcoal production while bamboo cutting was the main activity of the outside-households. Implementing community forestry practices may be a better option to reduce illegal dependence on selectively logged production forests. Moreover, supporting the right to extract NTFPs, such as bamboo, for commercial purposes from nearby production forests might be an incentive for the socio-economic development of forest-dependent rural people and the restoration of widespread degraded production forests in Myanmar.

Appendix I

Table S1 Hypothesized effects and references about the explanatory variables used in the regression models.

Variable	**Definition**	**Unit**	**Hypothesized effect**	**Literatures**
Age of head	Age of household head	Years	Positive	"Older rural people are assumed to have greater knowledge of the utilization and extraction of non-timber forest products (NTFPs) than younger ones and their dependence would therefore be higher." (Soe and Yeo-Chang, 2019)
Family size	Number of family members in the household	Persons	Positive	The more labor available, the more participation in labor intensive forest product extraction activities, accordingly the more dependence on forest. (Aung et al., 2015; Garekae and Thakadu, 2017; Soe and Yeo-Chang, 2019)
Farmland area (hectare)	Size of owned farmland	Hectare	Negative	Generally, wealthier households in Myanmar's rural communities owned larger size of land. The size of owned land has a negative effect on dependency on forest. (Moe and Liu, 2016; Soe and Yeo-Chang, 2019)
Total cash income (USD/year)	The sum of the cash income generated from the different sources of a household	USD/year	Negative	Higher total income with better income sources may be lower dependency on forest for cash income. (Mamo et al., 2007)

Duration of residence	Years of residence at the current living place	Years	Negative	“The longer households have lived in a village, the less likely they are to clear old-growth forest in part, because they have more secure usufruct rights to their land.” (Godoy et al., 1997)
Education	Education level of the household head	Primary (grade 1–4) Middle (grade 5-8) High (grade 9-)	Negative	Higher education creates better employment opportunities. Education level is expected to have a negative effect on dependency on forest for cash income. (Hlaing et al., 2017; Illukpitiya and Yanagida, 2008)
Accessibility to forest	The time to the reserved forests (RFs) to collect forest products	Bad (more than 1 day) Good (within 1day)	Positive	Better accessibility to forest may cause higher dependency on forest resources. (Khai et al., 2016; Win et al., 2018d)
House possession	A household owns a house for the permanent settlement	Own Not own	Negative	People with permanent settlement in Myanmar may be unlikely to be engaged in encroachment and may be less dependent on forests for their livelihoods, compared with people without permanent settlement. (Iftekhar and Hoque, 2005)
Knowledge about the law of RFs	Household head's knowledge about the prohibited access to RFs by Forest Law	Known Unknown	Negative	Having knowledge about the prohibited matter may drive one not to depend on forest for commercial purposes. (Htun et al., 2012)
Knowledge about the boundary of RFs	Household head's knowledge about the boundary of RFs	Known Unknown	Negative	Having knowledge about the boundary may drive not to depend on forest for commercial purpose. (Htun et al., 2012)

Chapter 3

Changes after logging ban in local people's dependency for cash income on selectively logged production forests in Myanmar

3.1. Introduction

In many tropical countries, rural households depend on adjacent forests for subsistence and cash income (Vedeld et al., 2007). Thus, conservation policies sometimes create conflicts for people living near or in forests (Maikhuri et al., 2001). Therefore, knowing how and to what extent local people depend on forests for their livelihoods is an important aspect of the sustainable management of forests (Sunderlin et al., 2005). Studies on dependence on forest income have been conducted in numerous countries, and comprehensive global reviews have found that forest income accounts for around 20% on average of total household income (Angelsen et al., 2014; Vedeld et al., 2007). However, despite a large body of literature on dependence on forest income, most studies have analyzed dependence at a single point in time, and have failed to analyze changes in the level of dependence over time in response to evolving pressures and opportunities (Jiao et al., 2017). Understanding changes in the level of dependence on forest income and changes in livelihood strategies over time is of great importance for policy-makers either developing new or modifying existing conservation and development strategies (Jiao et al., 2017).

Myanmar is a biodiversity hotspot in the Indo-Pacific region (Myers et al., 2000), and has one of the highest rates of forest cover (43.7% in 2020) among Southeast Asian countries (FAO, 2020). A total of 73% of the country's forest area is managed under permanent forest estates (PFEs), which include reserved forests (RFs), protected public forests (PPFs), and protected areas (PAs) (Forest Department, 1992). The RFs in Myanmar have made a significant contribution to the national economy through timber production under the Myanmar Selection System (MSS). RFs also play a vital role in supporting local people's livelihoods, especially by providing non-timber forest products (Soe and Yeo-Chang, 2019). However, deforestation and forest degradation have become critical issues in Myanmar, which was ranked seventh in the world in terms of average annual net loss of forest area over the period 2010–2020 (290,000 ha; FAO, 2020). Studies have revealed large-scale forest degradation in RFs (Mon et al., 2012; Win et al., 2018b). One of the main causes of forest degradation is illegal logging, which mainly occurs after legal logging operations have concluded. The number of illegally logged trees is much higher than that of legally logged trees (Khai et al., 2020b; Saung et al., 2021; Win et al., 2018d), as the construction of roads for the transportation of legally logged trees also provides ready access to the RFs for illegal logging (Win et al., 2018d).

Myanmar's forest laws prohibit local people from using RFs for commercial purposes, while subsistence use is allowed. However, national field surveys revealed that about 700,000 ha in RFs and PPFs had been encroached upon by local people (Forest Department, 2013). The household survey in 2013 revealed that households living inside RFs (encroachers) were mainly engaged in charcoal production for cash income, and their level of dependence on forest income was high (83% of total cash income) (Saung et al., 2020). In contrast, households living outside RFs mainly earned cash income from bamboo cutting in the RFs, and their level of dependence on forest income was relatively low at 32% of total cash income (Saung et al., 2020), but still higher than the average figure of around 20% in other countries (Angelsen et al., 2014; Vedeld et al., 2007).

In response to the increasing degradation of the RFs in Myanmar, a logging ban was introduced in 2016 for 1 year nationwide and 10 years in the Bago Yoma region, in which the study area is located. The logging ban meant that legal logging operations ceased, and strict prohibitions were placed on illegal logging activities in RFs. It was anticipated that there would be a reduction in illegal logging and local people's forest cash income would fall. However, there has been no evaluation of the effectiveness of the logging ban.

Thus, this study aims to understand changes in forest use strategies for cash income and the level of dependence on forest cash income of households living adjacent to RFs in Myanmar in response to the introduction of the logging ban in 2016. To this end, I used household survey data collected in 2013 and 2018. The results of my study are expected to contribute to further improvements in the implementation of the logging ban and/or other policy interventions in Myanmar, as well as in other countries.

3.2. Materials and Methods

3.2.1. Study area

The study was conducted in Bago Township, which is located in the Bago Yoma region in Myanmar between latitudes 17° 14′ N and 17° 50′ N and longitudes 96° 24′ E and 94° 41′ E (see Figure 3.1). Bago Yoma has a long history of production of teak and other hardwood timber species (Mon et al., 2012). Bago Township covers an area of 2905 km^2, of which about 53% is occupied by forests. The average annual rainfall and temperature are approximately 3360 mm and 27°C, respectively (Bago Forest Department, 2006). Moist upper mixed deciduous forest is the dominant forest type, with an abundance of teak (*Tectona grandis*), Pyinkado (*Xylia xylocarpa*), and other commercial species. The eight forested areas have been designated as RFs, and entering these areas and harvesting any forest products for commercial purposes without permission is strictly prohibited under the Forest Law (see Figure 3.1). Timber from these RFs has been harvested for the benefit of the national economy under the MSS since 1856.

Bago Township comprises one large city called Bago and 229 villages (see Figure 3.1). Of the 229 villages, three were located within the boundaries of the RFs, but these villages were officially approved and registered, and so I regarded them as being outside the RFs (see Figure 3.1). The population and number of households in Bago Township were 491,434 and 107,132, respectively, and 48.2% of the population lived in rural areas. The mean household size in the township was 4.4 people (Department of Population, 2015). It was found that 807 households were temporarily living within the RFs without permission, and these were regarded as encroachers (Forest Department, Bago Township, 2013). The study conducted in this area in 2013 by Saung et al. (2020) revealed that the main forest activity of most encroachers was year-round charcoal production, while many households living outside the RFs combined seasonal bamboo cutting with farming or small business operation. A logging ban was introduced in 2016 for 1 year nationwide and 10 years in the Bago Yoma region, including my study site, by way of a policy-based intervention.

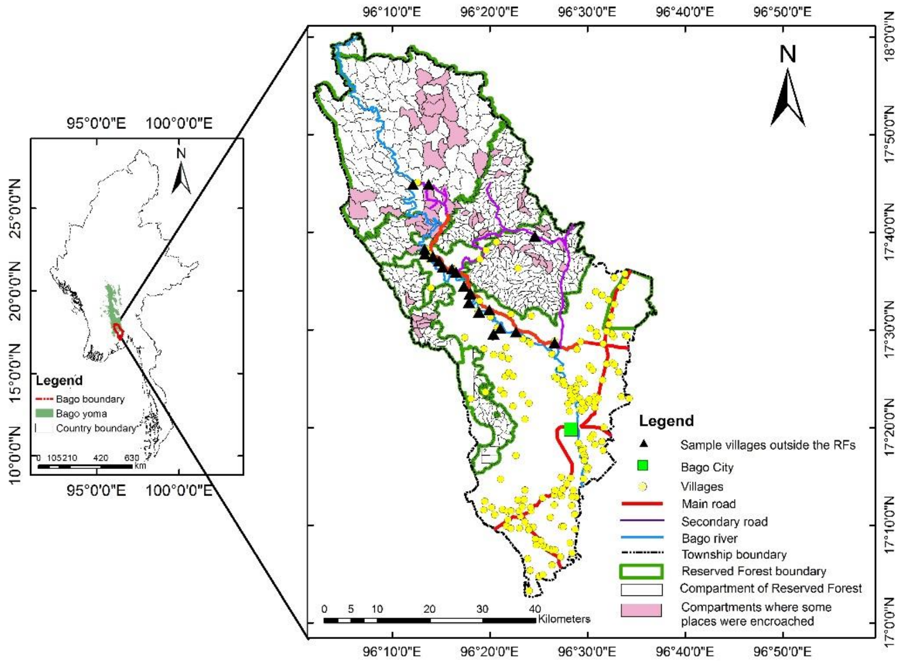

Figure 3.1. Location of study site in Bago Township, Myanmar.

3.2.2. Data collection

Data were collected in December 2013 and December 2018 from households located outside the RFs using a questionnaire and structured interviews with the head of each household. The research team consisted of both male and female undergraduate students and representatives from each selected village. Before interviews commenced, respondents were informed that the interview was only for academic research and was not related to any government authority. The questionnaire was presented in the national language for clarity, and was mainly focused on the local communities' knowledge of the nearby RFs, socioeconomic conditions, resource use patterns, and livelihoods.

In 2013, 19 of the 229 villages were selected as the sample for this study. All of these sample villages were situated either along a secondary road, which had been constructed mainly for use in official timber harvesting operations, or along the river, to cover different levels of access to the forests (see Figure 3.1). This road was able to be used by the local communities in summer (February–May) and winter (October–January), but during the rainy season (June–September), they had to use the Bago River running from north to south across Bago City for transportation. Therefore, in 2013, these villages had poor access to the city and markets for their products, and most residents had relatively low education and socioeconomic levels. All of these villages had been situated around the RFs for more than 80 years. Local communities only had access to the forests for their basic needs, and commercial use was prohibited by the Forest Law of 1992 (Forest Department, 1992).

In 2013, a total of 146 households, or 2.6% of the 5679 households in the 19 sample villages, were randomly selected. Before administering the questionnaire, I conducted a group discussion including the heads of the villages and elders who knew the villages well based on their experience in other villages to test the questions and to help determine the sampling intensity based on the level of heterogeneity or homogeneity among the various villages based on the people's livelihoods. Informal discussions were also conducted with the village heads, village elders, and respondents to gather more information to assist with my interpretation of the responses.

By 2018, the secondary road along which some of the 19 sample villages had been situated in 2013 had been upgraded to a main road that was able to be used by local communities all year round. Thus, in 2018, all of the sample villages had better access to the city and markets for their products. I aimed to conduct a follow-up survey of the 146 households that had been surveyed in 2013, but could only trace 85 (69%) of those households, either because they were absent as a result of temporary outside employment, or had moved to new locations, or could not be contacted. Therefore, I selected one new sample village with a total of 42 households that was located within an RF, and thus officially approved as a community forestry village. Next, 38 additional households (31% of the total sample), including 22 households from this new village and 16 additional households from two of the other officially approved villages that had been included in the 2013 survey, were randomly selected. The main objective of selecting additional households from the three officially approved villages outside the RFs was to include different levels of access to the forests and different village backgrounds. I then administered the questionnaire to the 123 households in the sample, and once again also conducted informal discussions with the village heads, village elders, and respondents to gather more information to assist with my interpretation of the responses.

3.2.3. Data analysis

Household income was divided into forest income and non-forest income. Forest income included income from activities within the RFs, such as collecting and/or producing forest products, labor, and farming within the RFs but did not include buying the forest products from someone else. Non-forest income included earnings from activities outside the RFs such as agriculture and small business. Some households earned only forest income or non-forest income, while others earned a combination of forest income and non-forest income. I identified a total of 16 different income strategies, as shown in Table 3.1.

Table 3.1. Income sources and household income strategies.

Cash income sources	Household cash income strategies	Households living outside the RFs in 2013 (n = 146)		Households living outside the RFs in 2018 (n = 123)	
		n	%	n	%
Only forest cash income	Only charcoal production	3	2.1	4	3.3
	Charcoal production and bamboo cutting	16	2.1	2	1.6
	Only bamboo cutting	4	2.7	2	1.6
	Only labor in RF	1	0.7		
Only non-forest cash income	Only agriculture	28	19.2	21	17.1
	Only business (opening shop in villages and small-scale animal husbandry)	13	8.9	5	4.1
	Other non-forest activities (labor in villages, combination of agriculture and business or labor in villages)	30	20.5	52	42.3
Combination of forest and non-forest cash income	Charcoal production and non-forest activities	5	3.4	8	6.5
	Charcoal production, bamboo cutting and non-forest activities	9	6.2	12	9.8
	Bamboo cutting and non-forest activities	31	21.2	8	6.5
	Farming in RF and non-forest activities	4	2.7	1	0.8
	Labor in RF and non-forest activities	2	1.4		
	Bamboo cutting, farming in RF and non-forest activities			1	0.8
	Charcoal production, salu cutting and non-forest activities			3	2.4
	Salu cutting and non-forest activities			3	2.4
	Timber production, bamboo cutting and non-forest activities			1	0.8
Total		146	100	123	100.0

Dependence on forest income was calculated as the ratio of forest income to total annual household income (Adam and Tayeb E L, 2014), where total household income was the sum of forest income and non-forest income. Products consumed directly by the household or given away to friends and relatives were treated as subsistence production and their value was excluded from annual household income. The exchange rates used to convert Myanmar Kyat to US dollars were (1 USD = 800 MMK) and (1 USD = 1500 MMK) in 2013 and 2018, respectively. Cash income from forest-based products and agriculture was based on productivity and selling prices, and the cost of all purchased inputs (such as purchased fertilizer and hired labor) was deducted to derive net income. Livestock income was defined as annual income from the sale of livestock.

Descriptive statistics were used to identify respondents' socioeconomic status, knowledge of the RFs, and level of dependence on the forests. I compared the overall means of eight continuous variables using Wilcoxon rank sum tests, and checked the homogeneity of five categorical variables using chi-square tests to analyze differences between the households surveyed in 2013 and those surveyed in 2018 (see Tables 3.2 and 3.3).

To analyze the factors influencing forest income (absolute value) and its proportion of total income (relative value), I developed two linear regression models for three different data sets; data obtained in both 2013 and 2018, data obtained in 2013, and data obtained in 2018. Forest cash income (USD/year) or forest cash income as a proportion of total income (%) was used as the dependent variable. Regarding independent variables, I used four continuous variables and six categorical variables, as shown in Tables 3.2 and 3.3, which covered household characteristics and knowledge of forest-dependent communities. Before applying the model, I checked for multi-collinearity among the independent variables and confirmed that there was no collinearity, with a variance inflation factor < 5 (Lonn et al., 2018). All statistical analyses were conducted using the R environment (R Core Team, 2019).

Table 3.2. Continuous variables for the socioeconomic characteristics of the sample households.

Continuous variables	Unit	Mean ± SD 2013 (n = 146)	Mean ± SD 2018 (n = 123)	Wilcoxon rank sum test
Total cash income	USD/year	1701 ± 1083	1519 ± 1400	p=0.0038
Forest cash income	USD/year	568 ± 874	198 ± 367	p=0.0001228
Non-forest cash income	USD/year	1133 ± 1027	1315 ± 1498	p=0.55
Forest cash income dependency	%	32 ± 38	21 ± 35	p=0.0105
Age of head	Years	47.1 ± 10.5	52.4 ± 10.2	p < 0.0001
Family size	Persons	5.4 ± 1.8	4.5 ± 2.1	p=0.0001
Farmland area	Hectare	2.3 ± 2.7	2.1 ± 3.2	p=0.3982
Duration of residence	Years	38.2 ± 16.0	38.1 ± 18.4	p=0.8539

Table 3.3. Categorical variables for the socioeconomic characteristics of the sample households.

Categorical variables	Definition	Classes	Share (%) 2013 (n = 146)	Share (%) 2018 (n = 123)	Chi-squared test
Education	Education level of the household head	Primary (grade 1–4)	75	75	$\chi^2 = 0.02912$ p = 0.9855
		Middle (grade 5–8)	17	18	
		High (grade 9–)	8	7	
Accessibility to forest	The time to the RFs to collect forest products	Bad (more than 1 day)	22	89	$\chi^2 = 116.42$ p < 0.00001
		Good (within 1 day)	78	11	
Knowledge about the law of RFs	Household head's knowledge about the prohibited access to RFs by Forest Law	Known	67	75	$\chi^2 = 1.5431$ p =0.2142
		Unknown	33	25	
Knowledge about the boundary of RFs	Household head's knowledge about the boundary of RFs	Known	54	74	$\chi^2 = 10.499$ p = 0.001195
		Unknown	46	26	
Knowledge about the logging ban	Household head's knowledge about the logging ban	Known		53	
		Unknown		47	

3.3. Results

3.3.1. Socioeconomic characteristics of households

Among the continuous variables, there were no differences in non-farm cash income, farmland area, and duration of residence between 2013 and 2018 (see Table 3.2). The households in 2018 had a lower total income (mean ± SD; 1519 ± 1400 USD/year) and forest cash income (198 ± 368 USD/year) than those in 2013 (see Table 3.2). The level of dependence on forest income was also lower in 2018 (21% ± 35%) than in 2013 (32% ± 38%). The households surveyed in 2018 tended to have older household heads and smaller families (see Table 3.2).

Among the categorical variables shown in Table 3.3, the largest difference between 2013 and 2018 was in relation to access to forests. Most households (89%) had poor access in 2018, while most (78%) had good access in 2013. The majority of households (74%) knew about the laws in relation to RFs in 2018, but only 50% knew about them in 2013, although only 50% of households in 2018 knew about the logging ban that had been introduced in 2016 (see Table 3.3).

3.3.2. Household cash income strategies

A total of 16 different household income strategies were found in 2013 and 2018, although the shares of households using these strategies differed significantly between 2013 and 2018 (chi-squared = 48.026, df = 15, $p < 0.0001$; see Figure 3.2 and Table 3.1). Four additional cash income strategies combining forest- and non-forest-related activities were observed among households in 2018. Generally, only non-forest activities (such as agriculture, small business, and combinations of different non-forest activities) showed an increase between 2013 and 2018 (49% to 64%), while forest-related activities (such as charcoal production, bamboo cutting, and combinations of forest- and non-forest-related activities) fell from 51% to 36% between 2013 and 2018 (see Figure 3.2 and Table 3.1). Among the forest-related activities, the share of bamboo-related activities fell from 41% in 2013 to 21% in 2018, while the share of charcoal-production-related activities remained steady at around 25% (see Figure 3.2 and Table 3.1).

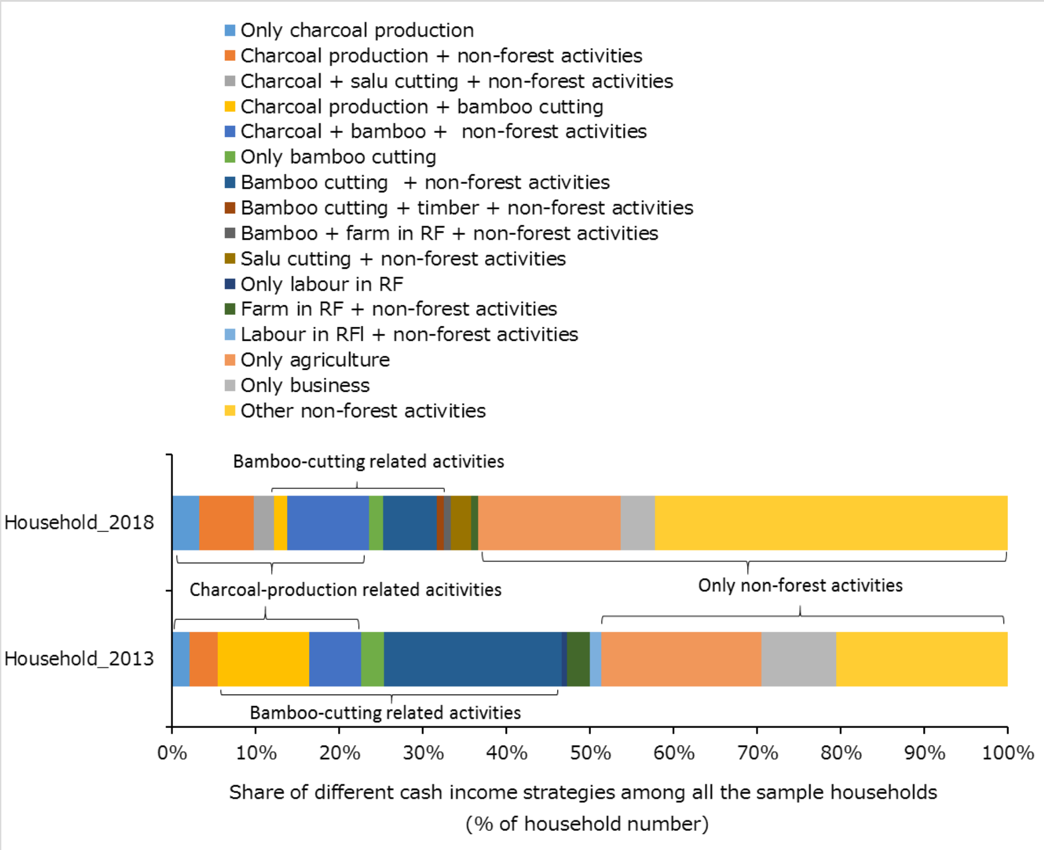

Figure 3.2. Shares of different cash income strategies among the sample households in 2013 and 2018.

3.3.3. Dependence on forest cash income

Total cash income was divided into eight forest income sources and three non-forest income sources (see Figure 3.3). The distribution of these 11 different income sources differed significantly between 2013 and 2018 (chi-squared = 27.033, df = 10, p = 0.002573; see Figure 3.3). There was a relatively large reduction in average cash income from combined charcoal production and bamboo cutting (290 to 87 USD/year) and bamboo cutting alone (171 to 33 USD/year) between 2013 and 2018, but the other sources of income did not change significantly (see Figure 3.3a). There was a relatively large increase in the share of income from other non-forest-related activities (35% to 57%), while there was a large decrease in bamboo-related income (see Figure 3.3b).

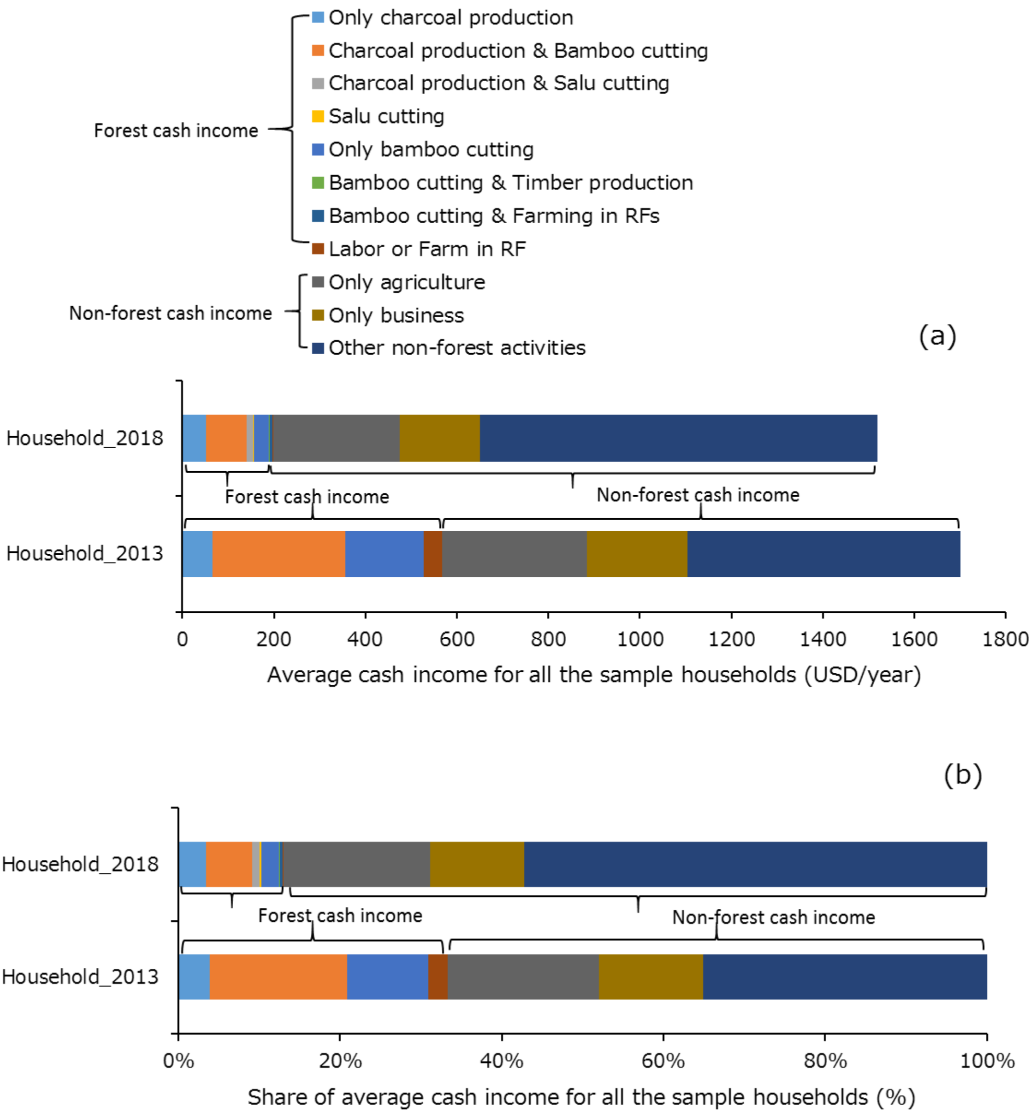

Figure 3.3. Average total cash income for the sample households divided into eight forest cash income sources and three non-forest cash income sources in (a) USD/year and (b) share of average total cash income.

3.3.4. Factors affecting dependence on forest income

Comparing the three regression models using data for both 2013 and 2018, data for 2013, and data for 2018 to analyze forest cash income, there were similarities in terms of significant factors (see Table 3.4). Farmland size had a significant negative effect ($p<0.05$) in all models. Duration of residence also had a negative effect on all models ($p<0.05$ for the model using data from both 2013 and 2018, and $p<0.1$ for the models using 2013 data and 2018 data). Access to forests had a positive effect on all models ($p<0.05$ for the model using data from both 2013 and 2018 and the model using 2013 data, and $p<0.1$ for the model using 2018 data). For the model using data from both 2013 and 2018, the categorical variable of the survey year (2013 or 2018) was not significant (p=0.110). As for knowledge of the laws and boundaries of the RFs, knowledge about the logging ban was not correlated with forest cash income (see Table 3.4).

The models used to analyze the level of dependence on forest cash income produced similar results (see Table 3.5) to those used to analyze the absolute values of forest cash income (USD/year) (see Table 3.4). For the model using data from both 2013 and 2018, the categorical variable of the survey year (2013 or 2018) was not significant (p=0.805), while age of household head, farmland area, duration of residence, and access to forests were all significant ($p<0.05$). For the model using 2018 data, knowledge about the logging ban was not correlated with dependence on forest cash income (see Table 3.5).

Table 3.4. Parameter estimates for the linear regression models analyzing forest cash income.

Coefficients	Model using all data in 2013 (n=146) and 2018 (n=123)				Model using data only in 2013 (n=146)				Model using data only in 2018 (n=123)			
	Estimate	Std. Error	*t v* alue	Pr (>|t|)	Estimate	Std. Error	*t v* alue	Pr (>|t|)	Estimate	Std. Error	*t v* alue	Pr (>|t|)
(Constant)	395.7112	255.8027	1.5470	0.1231	338.9390	415.8160	0.8150	0.4164	3.11E+02	206.7767	1.503	0.136
Year of survey (2018)	-181.1776	112.8301	-1.6060	0.1096	NA	NA	NA	NA	NA	NA	NA	NA
Age of head (Years)	-0.7842	4.3408	-0.1810	0.8568	4.621	7.997	0.5780	0.5643	-4.2521	3.38	-1.258	0.211
Family size (Persons)	22.611	21.388	1.0570	0.2914	6.437	42.996	0.1500	0.8812	27.4735	15.2183	1.805	0.074
Farmland area (hectare)	-47.6615	15.2753	-3.1200	0.0020	-72.936	29.163	-2.5010	0.0136	-26.7656	10.8176	-2.474	0.015
Duration of residence (Years)	-5.8581	2.7316	-2.1450	0.0329	-9.507	4.945	-1.9220	0.0566	-4.0014	2.0869	-1.917	0.058
Education (Middle)	24.2232	177.6534	0.1360	0.8917	73.0220	301.7920	0.2420	0.8092	-0.8089	140.4693	-0.006	0.995
Education (Primary)	137.3331	158.4914	0.8670	0.3870	205.9000	274.3990	0.7500	0.4543	39.5285	123.4081	0.320	0.749
Accessibility to forest (Good)	274.7677	109.6753	2.5050	0.0129	349.4300	168.587	2.0730	0.0401	194.6401	104.2388	1.867	0.065
Knowledge about the law of RFs (Known)	171.4338	105.97	1.6180	0.1069	250.1620	187.315	1.3360	0.1839	18.9668	83.6698	0.227	0.821
Knowledge about the boundary of RFs (Known)	-26.7378	100.8761	-0.2650	0.7912	-182.35	172.197	-1.0590	0.2915	143.255	82.9484	1.727	0.087
Knowledge about the logging ban (Known)	NA*	NA*	NA*	NA*	NA*	NA*	NA*	NA*	43.573	66.2619	0.658	0.512
	R^2 = 0.1882				R^2 = 0.1636				R^2 = 0.2093			
	Adjusted R^2 = 0.1567				Adjusted R^2 = 0.1083				Adjusted R^2 = 0.1387			
	F value = 5.981				F value = 2.956				F value = 2.964			
	p value < 0.00001				p value = 0.00307				p value = 0.002409			

Note; NA* indicates that this variable was not used for regression because logging ban was introduced in 2016.

Table 3.5. Parameter estimates for the linear regression models analyzing the level of dependence on forest cash income (forest cash income divided by total cash income).

Coefficients	Model using all data in 2013 (n=146) and 2018 (n=123)				Model using data only in 2013 (n=146)				Model using data only in 2018 (n=123)			
	Estimate	Std. Error	*t* value	Pr (>|t|)	Estimate	Std. Error	*t* value	Pr (>|t|)	Estimate	Std. Error	*t* value	Pr (>|t|)
(Constant)	0.4395	0.1286	3.4180	0.0007	0.3491	0.1712	2.0390	0.0434	5.45E-01	0.1902	2.867	0.005
Year of survey (2018)	-0.0140	0.0567	-0.2460	0.8057	NA	NA	NA	NA	NA	NA	NA	NA
Age of head (Years)	-0.004355	0.002182	-1.9960	0.0470	-0.000738	0.003293	-0.2240	0.8230	-0.007224	0.003109	-2.324	0.022
Family size (Persons)	0.016301	0.010751	1.5160	0.1307	-0.005354	0.017703	-0.3020	0.7628	0.025112	0.013997	1.794	0.076
Farmland area (hectare)	-0.036564	0.007678	-4.7620	0.0000	-0.037992	0.012007	-3.1640	0.0019	-0.032627	0.00995	-3.279	0.001
Duration of residence (Years)	-0.003592	0.001373	-2.6160	0.0094	-0.004438	0.002036	-2.1800	0.0310	-0.003136	0.001919	-1.634	0.105
Education (Middle)	0.0567	0.0893	0.6350	0.5261	0.0950	0.1243	0.7650	0.4458	0.00692	0.1292	0.054	0.957
Education (Primary)	0.0755	0.0797	0.9480	0.3441	0.1317	0.1130	1.1660	0.2458	0.009027	0.1135	0.080	0.937
Accessibility to forest (Good)	0.1132	0.055129	2.0540	0.0410	0.1342	0.069412	1.9340	0.0552	0.112468	0.0959	1.173	0.243
Knowledge about the law of RFs (Known)	0.0993	0.053267	1.8640	0.0634	0.1846	0.077123	2.3940	0.0180	-0.006056	0.0770	-0.079	0.937
Knowledge about the boundary of RFs (Known)	0.005379	0.050706	0.1060	0.9156	-0.088921	0.070898	-1.2540	0.2119	0.097929	0.0763	1.284	0.202
Knowledge about the logging ban (Known)	NA*	NA*	NA*	NA*	NA*	NA*	NA*	NA*	0.064094	0.0609	1.052	0.295
	R^2 = 0.2235				R^2 = 0.2373				R^2 = 0.2468			
	Adjusted R^2 =0.1934				Adjusted R^2 = 0.1868				Adjusted R^2 = 0.1796			
	F value = 7.427				F value = 4.701				F value = 3.67			
	p value < 0.00001				p value < 0.00001				p value = 0.0002895			

Note; NA* indicates that this variable was not used for regression because logging ban was introduced in 2016.

3.4. Discussion

3.4.1. Changes in household cash income after the introduction of the logging ban

Cash income strategies among households changed significantly between 2013 and 2018 following the introduction of the logging ban in 2016. The major change I identified was a decrease in forest-related activities, especially bamboo-related activities, and an increase in non-forest-related activities (see Figure 3.2). Informal discussions with survey respondents suggested that this was because of the reduced access to the forests under the strict new laws. My interview-based data confirmed that access to the forests was significantly reduced after the introduction of the logging ban, with the share of households with good access (i.e., located less than 1 day's travel from the forest) falling from 78% to 21% (see Table 3.2). Among the non-forest activities, the shares of various types of combinations of activities rather than solely either agriculture or small business increased significantly (see Table 3.1 and Figure 3.2). This is consistent with the evidence that diversification is important in relation to maintaining rural livelihoods by minimizing the adverse effects of the prevailing risks in rural economies (e.g., shocks in the form of droughts, floods, and policy changes) (Walelign and Jiao, 2017).

Total cash income and the share of forest cash income both decreased significantly following the introduction of the logging ban (see Table 3.2). These decreases were likely the result of the reduction in forest cash income because non-forest cash income did not change over time (see Table 3.2). A decreasing trend in forest income was also reported in rural Cambodia from 2008 to 2012, where economic land concession-associated deforestation and forest degradation resulted in loss of access to forest products (Jiao et al., 2017). Jiao et al.'s findings also confirmed the importance of access to and availability of forests for local people. In a case study from 2009 to 2012 in Nepal, both forest income and total environmental income increased, implying that the availability of forest resources was greater in the study area in Nepal than in rural Cambodia and in my study area in Myanmar.

In my study, non-forest cash income did not increase over time (see Table 3.2), even though the share of households engaged in non-forest-related activities increased (see Figure 3.2). In the case of rural Cambodia, non-farm income more than doubled, while forest income and farm income fell between 2009 and 2012 because of the transition to an open market economy and the rapid development of the garment manufacturing and construction industries (Jiao et al., 2017). In the case study in Nepal, there was a relatively large increase in business income between 2009 and 2012, while crop-related income fell significantly (Walelign and Jiao, 2017). These case studies imply that there were far fewer opportunities for cash income generation from non-forest and non-farm activities in Myanmar than in Cambodia and Nepal. These limited opportunities might be the reason for the lack of increase in non-forest cash income despite the reduced access to forests following the introduction of the logging ban.

3.4.2. Factors affecting forest cash income

I used six regression models to analyze the absolute and relative values of forest cash income using three different data sets; data from both 2013 and 2018, data from 2013, and data from 2018. The results were similar among the six models. In the models using pooled data from both 2013 and 2018, the survey year (2013 or 2018) was not a significant factor, indicating that the time difference cannot explain variations in forest cash income. Rather, I found three factors (farmland area, duration of residence, and forest accessibility) that were consistently significant in relation to models for both forest cash income (see Table 3.4) and the proportion of total income it represented (see Table 3.5). Farmland size and duration of residence were negatively correlated with forest cash income. This supports the hypothesis that additional income generated from agriculture can reduce dependence on forest income (Saung et al., 2020). Previous studies have found that limited access to agricultural land increases people's dependence on forest income (Jain and Sajjad, 2015; Kamanga et al., 2009). Regarding duration of residence, this supports the hypothesis that households that have spent a longer period of time in a village may have more secure rights to the use of their land, and thus may be less dependent on forest income (Saung et al., 2020). A positive correlation between access to the forest and the level of dependence on forest income is consistent with the finding of a Cameroon case study confirming that easy access to forest resources increased dependence on forest income (Mukete et al., 2018). Of these three key factors (farmland area, duration of residence before and after the logging ban, and access to the forest), farmland area and duration of residence did not change (see Table 3.2), whereas access to the forest was significantly reduced following the introduction of the logging ban. Therefore, I can conclude that the driving force behind the decline in forest cash income from 2013 to 2018 was the reduced access to the forest following the introduction of the logging ban in 2016. This is in line with the information revealed during informal discussions mentioned above and the findings of the study in rural Cambodia (Jiao et al., 2017).

Even though forest cash income fell to an average of 21% of total cash income after the introduction of the logging ban, this level was not significantly lower than elsewhere in Myanmar and in other countries. For example, the figure in 10 villages near the production forests in the Bago Yoma region in Myanmar, the same region examined in the present study, was 25% (Khaine et al., 2014b). Vedeld et al. (2007), who analyzed 51 case studies from 17 countries, found that on average, forest environmental income accounted for 22% of total income. Although the Myanmar Forest Law prohibits local people from using the RFs for commercial purposes, I found that around 20% of households were engaged in charcoal-production or bamboo-related activities in 2018, despite the introduction of the logging ban in 2016 (see Figure 3.2), suggesting a shortage of opportunities for local people to generate cash income. Thus, development projects, coupled with agricultural intensification, agroforestry, or community forestry, may be required to enable households to generate more cash income while reducing their dependence on RFs.

Additionally, in 2018, about half of all households were unaware of the logging ban that had been introduced in 2016, even though most of them (89%) faced difficulties in accessing the forests (see Table 3.2). Furthermore, in 2018, knowledge about the logging ban was not a significant factor in relation to dependence on forest income (see Tables 3.4 and 3.5). These results suggest that extension activities are required in relation to both new and existing policy-based interventions.

3.4.3. Study limitations

The major limitation of my study was the small sample size of 85 households that I was able to survey in both 2013 and 2018. This lack of paired data over time hampered my efforts to analyze differences over time in each household, as per Walelign and Jiao, (2017) and Jiao et al., (2017). Instead, after adding new sample households in 2018, I was forced to treat 2013 data (n=146) and 2018 data (n=123) as two different populations. Furthermore, because of the small sample size, I did not classify households into different groups based on livelihood strategies or income levels. Thus, future research should be undertaken using a larger sample to enable changes in dependence on forest income over time to be analyzed in relation to different types of households (Jiao et al., 2017; Walelign and Jiao, 2017).

3.5. Conclusions

The results of this study confirmed that after the introduction of the logging ban in 2016, households located adjacent to RFs experienced a reduction in both forest cash income and total cash income, while non-forest cash income remained unchanged. Farmland size, duration of residence, and access to the forests all had a significant influence on the level of dependence on forest cash income. Of these factors, only access to the RFs changed after the introduction of the logging ban, with the reduced access leading to reduced dependence on the RFs for income generation. Nevertheless, I also found that a significant number of households continued to depend on the RFs for income generation through activities such as charcoal production and bamboo cutting. Thus, rural development projects are needed to provide increased opportunities for income generation, while extension activities are also required to increase the effectiveness of policies such as the logging ban in Myanmar.

Chapter 4

Condition of illegally logged stands following high frequency legal logging in Bago Yoma, Myanmar

4.1. Introduction

Approximately 20% of natural tropical forests are classified as production forests, where selective logging is a common practice for timber production (Blaser et al., 2011). Tropical production forests supply both timber and non-timber forest products (Guariguata et al., 2010; Rist et al., 2012). Additionally, there is a growing focus on the conservation values of tropical production forests in terms of various ecosystem services (Berry et al., 2010; Edwards et al., 2014; Putz et al., 2012). However, selectively logged production forests are often degraded because of over-harvesting and/or large disturbances to the remaining trees and the ground (Asner et al., 2006; Mon et al., 2012; Pereira et al., 2002). In degraded forests, understory vegetation such as grasses and bamboos can become dominant, resulting in negative impacts on tree regeneration (Larpkern et al., 2009; Panadda et al., 2011). The restoration of degraded forests has become increasingly important (Chazdon, 2008; Lamb et al., 2005; Philipson et al., 2020). As the first step for restoring degraded production forests, it is necessary to identify the different states of degradation, such as the remaining stock and regeneration status of commercial tree species in relation to understory vegetation (Chazdon, 2008; Fadrique et al., 2021; Tálamo et al., 2020).

Myanmar has a long history of applying selective logging, called the Myanmar Selection System (MSS), in tropical mixed deciduous forests, where teak (*Tectona grandis*) and pyinkado (*Xylia xylocarpa*) are the main high-quality timber species (Khai et al., 2016). An important feature of the MSS is the use of elephants to drag logs from the felling sites to log landings (skidding). Khai et al. (2020b) revealed that elephant skidding contributes the lowest level of ground disturbance compared with using bulldozers for skidding, as is performed outside Myanmar. This long history of low-impact logging using elephants suggests that the MSS could be a good practice for sustainable forestry. However, studies have revealed widespread forest degradation in selectively logged production forests in Myanmar (Mon et al., 2012; Win et al., 2018b). The major reasons for degradation include over-harvesting because of shorter rotation periods than the MSS standard of 30 years and illegal logging that often occurs after legal logging operations (Khai et al., 2016; Mon et al., 2012; Win et al., 2018d). Khai et al. (2016) indicated that there were two types of illegal logging: one for sawn timber production and the other for charcoal making. Illegal logging for timber targeted a small number of large trees, focused on two high-quality timber species, teak and pyinkado (Khai et al., 2020b, 2016; Win et al., 2018d). This type of illegal logging was found in better condition stands in compartments with a longer cycle of legal logging (Khai et al., 2016). In contrast, illegal logging for charcoal targeted different sized trees of various species, and this practice was found in a degraded, bamboo-dominated stand in the compartment with inappropriately short cycles of legal logging (Khai et al., 2016). Thus, the impacts of illegal logging on remaining tree stocks and species composition may differ between the two types of illegal logging.

This present study aimed to further understand the structure of illegally logged stands in compartments with inappropriately frequent legal logging cycles in Myanmar. My working hypothesis is that illegal logging in compartments under high frequent legal logging may occur mainly for charcoal making, and bamboo dominance may be related to reduced tree density. While Khai et al. (2016) investigated a single sample plot (1 ha) without replication, I conducted field measurements in four plots each measuring 0.64 ha (80 m × 80 m) in compartments with a high frequency of legal logging, where people were illegally settled.

4.2. Materials and Methods

4.2.1. Study area

My study sites were located in South Zamaye Reserved Forest (RF), Bago Township, in the southeast of Bago Yoma, Myanmar (Figure 4.1). Bago Yoma has the longest history of timber production using the MSS in the country. There are three seasons each year: "hot" from February to May, "rainy" from June to September, and "dry" from October to January. The mean annual rainfall is 3360 mm with an average humidity of 82.9%, and the mean annual temperature is 26.7 °C in the Bago District. Bago Township covers 2905 km^2, of which around 53% is forested. The dominant forest type is a moist upper mixed deciduous forest where teak, pyinkado, and other commercial species can be found along with bamboo species.

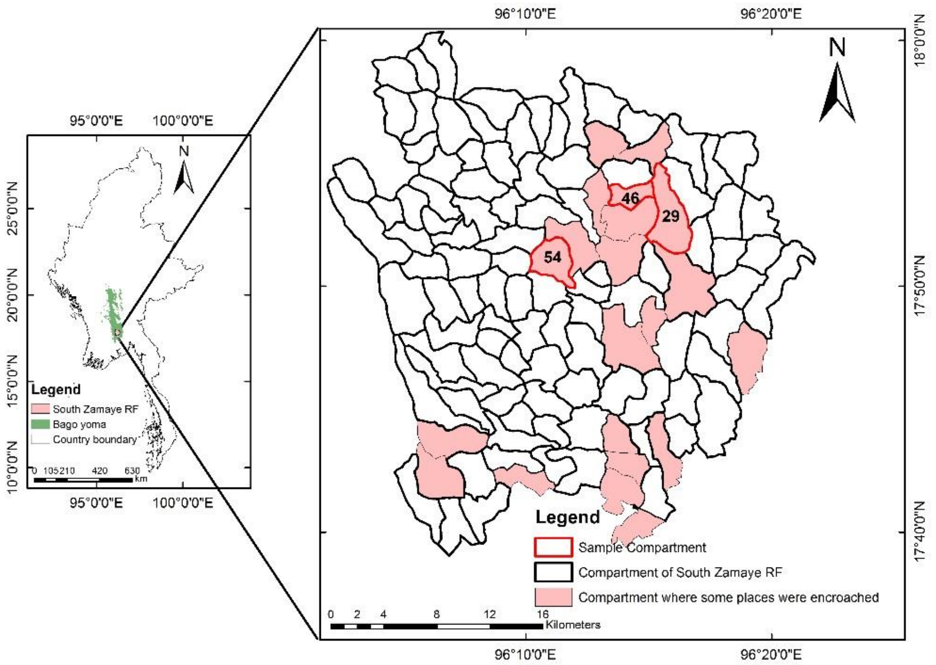

Figure 4.1. Location of study sites in South Zamaye Reserved Forest (RF), Bago Township, Myanmar.

South Zamaye RF covers 79,613 ha, including 119 compartments (Figure 4.1). At the time of my field survey in 2013, official harvesting operations were being practiced in this RF. Among the 119 compartments, 21 were encroached by a total of 336 households in 2013 (Figure 4.1). To establish the sample plots, I intentionally selected three compartments (29, 46, and 54) where the latest logging operation was conducted in 2011, the frequency of legal logging was higher than the MSS standard 30-year rotation cycle (e.g., logging occurred once in 30 years), and people had encroached and illegally settled (Forest Department, Bago Township, 2013). The Myanmar forest law prohibits the settlement and commercial use of the RF and PPF without permission, while subsistence use is allowed in designated areas (Forest Department, 1992).

In compartment 29, with an area of 1238 ha, legal logging was practiced in 1999, 2000, 2004, 2009, and 2011; a total of 6053 trees, equal to 11,694.13 m^3 of timber, were harvested; and 41 households have been living temporarily in this compartment since 2010–2012 (Forest Department, Bago Township, 2013). In compartment 46, with an area of 429 ha, legal logging was conducted in 1995, 2000, and 2011; a total of 3518 trees, equal to 11,912.89 m^3 of timber, were harvested; and 32 households have been resident temporarily since 2011–2012. In compartment 54, covering 741 ha, legal logging was carried out in 1997, 2007, and 2011; a total of 3027 trees, equal to 7455.67 m^3, were harvested; and encroachments were found only in 2013 (FD Bago, 2013).

4.2.2. Legal logging operations under the MSS

Under the MSS, logging is operated in compartments, which are basic units that yield approximately equal volumes of timber products in a 30-year felling cycle (Mon et al., 2012). Staff of the Myanmar Forest Department (FD) select and mark trees to be cut following the prescribed minimum diameter cut limits (MDCL). Then, felling the marked trees and skidding operations are carried out by Myanmar Timber Enterprise (MTE) or its subcontracting agent, or both, normally from July to December. Forest roads for log transportation are usually constructed at the end of the rainy season, generally after November when the soil hardens. These roads are usable only in the dry season.

The MDCL depends on species; for example, diameter at breast height (DBH) is 78 cm for teak, *Dipterocarpus* spp., *Hopea odorata*, *Anisoptera scaphula*, and *Parashorea stellata*; 68 cm for pyinkado, *Lagerstroemia speciosa*, and *Lagerstroemia tomentosa*; and 58 cm for other hardwood species. Tree species are classified into six commercial species groups: teak and Groups I–V depending on the commercial value. Teak represents the most valuable product; commercial value as timber decreases from Group I through V. Pyinkado, *Pentacme siamensis*, and *Dalbergia oliveri* are the representative species of Group I, and Group V has lesser-used species. During selecting and cutting the trees, the FD and MTE staff put hammer marks on the remaining stumps and cut logs to ensure the legality of logging operations. Hammer-marked information on the stump surface includes the tree number, log number from the single tree, and the code of the person in charge. FD has to inspect hammer marks put on the stumps and the logs during harvesting of the marked trees and transporting the logs to ensure the legality of logging operations. After finish logging operations, MTE needs to destroy the logging road constructed during logging operations following the MSS regulation. Then, MTE has to report to FD about the completion of logging operations and leaving the working RF or Compartment. FD has to inspect whether MTE follows the prescribed rules in logging operations as a final check.

4.2.3. Field measurements and data analysis

Data collection was conducted in December 2013 and January 2014. The four permanent sample plots (80 × 80 m) were set up; one plot each in compartments 29 (Plot 1) and 54 (Plot 4) and two in compartment 46 (Plots 2 and 3) (Figure 4.1, Table 4.1). The reason for establishing one more plot in the smallest compartment (46) is because I noticed relatively large variations in stand structure within this compartment. To set up each sample plot, a starting point was selected to include illegally logged stumps or legally logged ones, or both, to represent a production stand. Then, the base line and grid lines were laid down in north to south and east to west directions from this starting point. Each plot was divided into four subplots (40 × 40 m). In each plot, all standing trees ≥ 10 cm DBH were tagged, identified, and their DBH was measured. The following details were recorded for all bamboo clumps: the number of culms per clump (n), and the maximum and minimum culm diameter (D_{max} and D_{min}). The basal area of the ith bamboo clump (BA_i) was calculated as (Thein et al., 2007):

$$BA_i = n \times D_{max} \times D_{min} \times \pi/40000$$

All stumps were also measured for their diameter at cut height, and the local name of the species was identified by the aid of FD staff and local people. All recorded trees, stumps, and bamboos with their local name were then confirmed using the checklist of Kress and Lace (2003). Legal stumps were distinguished by judging whether the MSS rules of logging operations were followed or not; for example, if the diameter of the cut trees was larger than the MDCL, stump height was lower than 0.4 m, and the hammer sign was present on the stumps (see the photographs in Supplementary Material Figure S1) (Khai et al., 2016; Win et al., 2018d). The DBH_i of ith extracted tree was estimated using the stem shape model (Thein et al., 2007):

$$DBH_i = d_i/(1.028\ h_i^{-0.114})$$

where d_i and h_i are the diameter and height of the ith stump, respectively. I also distinguished old stumps that were legally or illegally cut before 2011 from new stumps that were cut legally in 2011. It was not difficult with help from local people and FD staff to distinguish old and new stumps based on their texture and condition (Win et al., 2018d). For data analysis, I only used stumps that were legally cut in 2011 and that were illegally cut from 2011 to 2013.

Using data from the field measurements in 2013 on the legal and illegal stumps and living trees, I reconstructed the stand structure just before and after official logging in 2011. For this, I did not consider the DBH increment when I reconstructed the DBH in 2011 from DBH measurements in 2013 because of limited information on the diameter increment of each species.

Studies have shown that illegal logging often targets the larger trees of specific commercial species (Toyama et al., 2015; Win et al., 2018d). To examine such effects, I applied a generalized linear model (GLM) with a binomial distribution and a logit link function. The dependent variable was whether the tree was standing (0) or had been cut illegally, and the independent variables were DBH (cm), quality for timber, and quality for charcoal (1 (best), 2, 3, 4 (worst)). The grading of the quality for timber and charcoal was conducted in consultation with local people and local FD staff (see the grading definition and species list in Supplementary Material Table S1). I also applied a GLM with a Poisson distribution and a log link function to confirm whether the number of trees was related to the number of bamboo clumps in the remaining stands. For this, I tested two levels of data: one for the plot level (n = 4, each 0.64 ha) and the other for the subplot level (n = 16, each 0.16 ha). In the Poisson GLM, I used tree counts in the surveyed area (0.64 or 0.16 ha) as the response variable, bamboo clump density (clumps ha^{-1}) as the explanatory variable, and log of the surveyed area as the offset. All statistical analyses were conducted using the R environment (R Core Team, 2019).

Table 4.1. Stand structure before and after the latest legal logging in 2011, and legally and illegally cut trees in four plots.

Attributes	Plot 1	Plot 2	Plot 3	Plot 4
Stand structure prior to the latest official logging in 2011				
Tree density (trees ha^{-1})	100.0	54.7	212.5	154.7
Mean tree DBH (cm)	43.8	52.0	27.3	34.5
Tree BA (m^2 ha^{-1})	18.1	15.5	15.3	19.4
Tree species richness (counts 0.64-ha^{-1})	16	19	22	23
Legal cut trees in 2011				
Cut-tree number (trees ha^{-1})	4.7	1.6	0.0	10.9
Mean cut-tree DBH (cm)	69.9	103.0	0.0	83.9
Cut-tree BA (m^2 ha^{-1})	1.9	1.3	0.0	6.1
Cut-tree species number (counts 0.64-ha^{-1})	1	1	0	2
Illegal cut trees from 2011 to 2013				
Cut-tree number (trees ha^{-1})	31.3	20.3	31.3	14.1
Mean cut-tree DBH (cm)	50.4	59.2	44.1	38.5
Cut-tree BA (m^2 ha^{-1})	6.7	6.6	5.1	1.9
Cut-tree species number (counts 0.64-ha^{-1})	7	9	7	6
Stand structure of remaining stands in 2013				
Tree density (trees ha^{-1})	64.1	32.8	181.3	129.7
Mean tree DBH (cm)	38.6	45.1	24.4	29.9
Tree BA (m^2 ha^{-1})	9.5	7.6	10.1	11.4
Tree species richness (counts 0.64-ha^{-1})	15	15	22	23
Bamboo clump density (clumps ha^{-1})	54.7	145.3	6.3	17.2
Bamboo clump BA (m^2 ha^{-1})	4.4	7.8	0.5	1.1

4.3. Results

4.3.1. Stand structure prior to the latest legal logging in 2011

Stand structure prior to the latest legal logging, which was conducted in 2011, was different among the four plots (Table 4.1). Stocks ranged from 54 to 212 trees ha^{-1} for tree density and from 15.3 to 19.4 m^2 ha^{-1} for tree basal area. Species richness varied from 16 to 23 species 0.64 ha^{-1}.

The DBH distribution was also different among the four plots: an inverse-J shape for plots 3 and 4, a single peak for plot 1, and uniform in plot 2 (Figure 4.2). The composition of the commercial species groups also varied. The relative dominance in tree numbers, except for Group V, was found to be teak for plot 3, Group I for plot 2, Group II for plot 1, and Group III for plot 4 (Table 4.2, Figure 4.2).

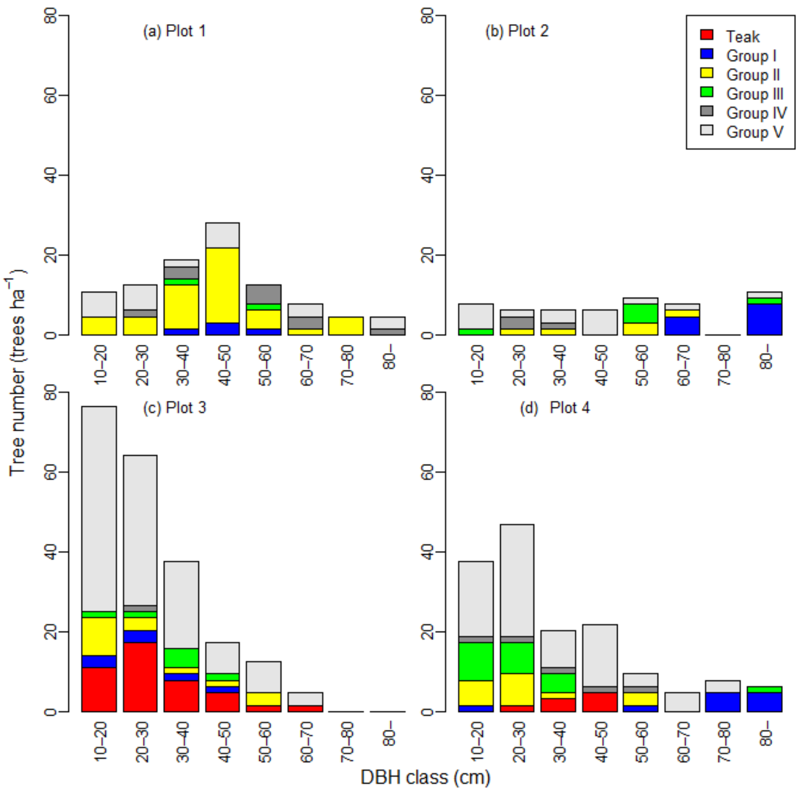

Figure 4.2. Diameter at breast height (DBH) distribution prior to the latest legal logging for commercial species groups in the four plots for plots 1 (a) to 4 (d).

Table 4.2. Tree density (ha^{-1}) for each species group before and after the latest legal logging in 2011, and legally and illegally cut tree in four plots.

Species group	Prior to the latest official logging in 2011				Legally cut trees in 2011				Illegally cut trees from 2011 to 2013				Remainig Stand in 2013			
	Plot 1	Plot 2	Plot 3	Plot 4	Plot 1	Plot 2	Plot 3	Plot 4	Plot 1	Plot 2	Plot 3	Plot 4	Plot 1	Plot 2	Plot 3	Plot 4
Teak	0.0	0.0	43.8	9.4	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	42.2	9.4
Group I	6.3	12.5	9.4	12.5	0.0	1.6	0.0	9.4	6.3	6.3	6.3	1.6	0.0	4.7	3.1	1.6
Group II	50.0	7.8	18.8	18.8	0.0	0.0	0.0	0.0	15.6	3.1	4.7	3.1	34.4	4.7	14.1	15.6
Group III	3.1	7.8	9.4	23.4	0.0	0.0	0.0	1.6	1.6	1.6	1.6	3.1	1.6	6.3	7.8	18.8
Group IV	14.1	4.7	1.6	7.8	4.7	0.0	0.0	0.0	0.0	3.1	0.0	0.0	9.4	1.6	1.6	7.8
Group V	26.6	21.9	129.7	82.8	0.0	0.0	0.0	0.0	7.8	6.3	17.2	6.3	18.8	15.6	112.5	76.6
Total	100.0	54.7	212.5	154.7	4.7	1.6	0.0	10.9	31.3	20.3	31.3	14.1	64.1	32.8	181.3	129.7

4.3.2. Legally and illegally cut trees

For legal cutting, felling intensities were from 1.6 to 10.9 trees ha^{-1} in three of the plots; in plot 3, no legally cut stumps were found (Table 4.1). The species of the cut trees were *Xylia xylocarpa* (Group 1) in plots 2 and 4, *Garuga pinnata* (Group 4) in plot 1, and *Terminalia tomentosa* (Group 3) in plot 4 (Tables 4.1 and 4.2). The average DBH was from 69.9 to 103.0 cm (Table 4.1, Figure 4.2).

For illegal cutting, the number of cut trees ranged from 14.1 to 31.3 trees ha^{-1} (Table 4.1), and the mean DBH varied from 38.5 to 59.2 cm among the four plots. The number of illegally cut tree species varied from 6 to 9 in the 0.64-ha plots (Table 4.1). These were classified into various species groups (Table 4.2).

The GLM model for illegal logging indicated that the likelihood of illegal logging was higher for larger trees and species of higher quality for charcoal making (Table 4.3). In contrast, the quality for timber was not selected as an explanatory variable in the model.

Table 4.3. The result of the generalized linear model (GLM) with logit link to predict probabilities of illegal logging for a given tree.

Variable	Estimate	Std. Error	Z-Value	Pr (>|Z|)
Intercept	-1.6112	0.5568	-2.8940	0.0038
DBH (cm)	0.0306	0.0069	4.4140	<0.00001
Quality for charcoal	-0.7108	0.1714	-4.1470	<0.00001
Quality for timber	0.1770	0.1309	1.3520	0.176

The response variables are 1 and 0 for illegally logged trees and remaining trees, respectively. Quality for charcoal and timber is classified into four classes, with decreasing quality from 1 to 4.

4.3.3. The remaining stands in 2013

The structure of the remaining stands after legal and illegal cutting differed among four plots (Figure 4.3). Tree density ranged from 32.8 to 181.3 trees ha^{-1} and the BA for trees varied from 7.6 to 11.4 m^2 ha^{-1} (Table 4.1). Bamboo clump density was also very different among the four plots (Figure 4.4), ranging from 6.3 to 145.3 clumps ha^{-1} (Table 4.1). A significant negative relationship was found between tree density and bamboo clump density both at the plot (n = 4) and subplot (n = 16) levels (Figure 4.5, Supplementary Material Table S2).

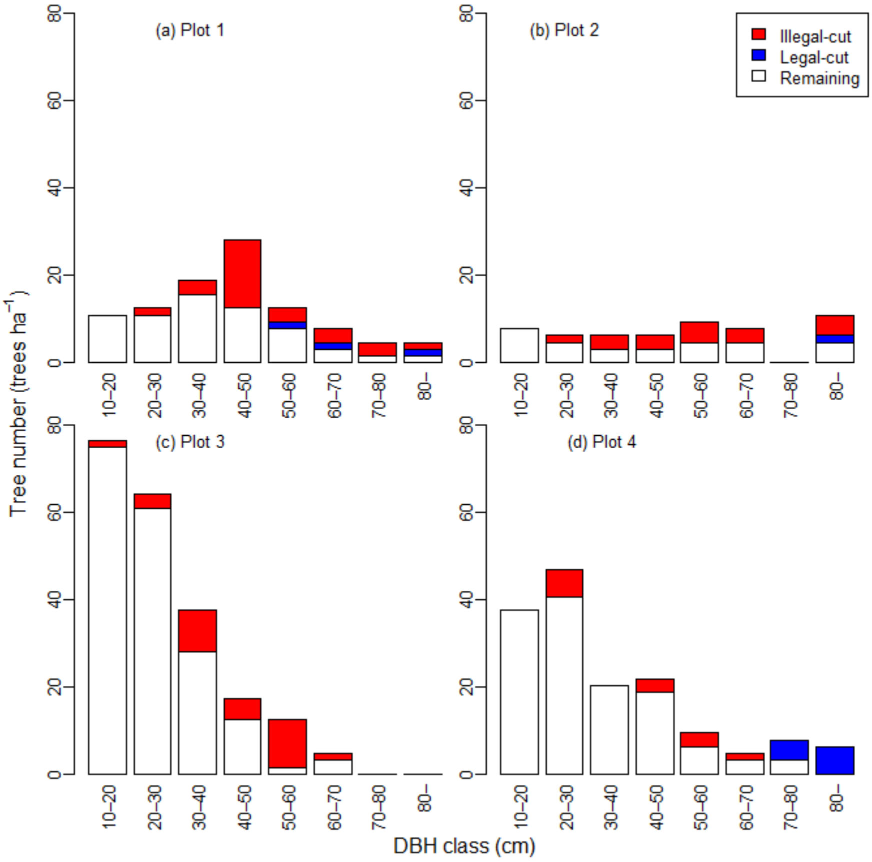

Figure 4.3. Diameter at breast height (DBH) distribution prior to the latest legal logging in 2011 and the classification after the legal logging up 2013 for plots 1 (a) to 4 (d).

Plot 1

Plot 2

Plot 3

Plot 4

Figure 4.4. Photographs of the four plots in December 2013 and January 2014.

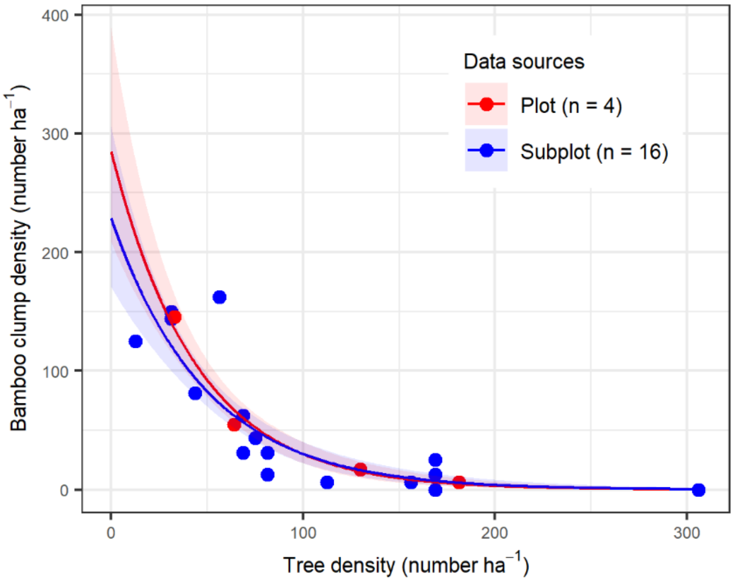

Figure 4.5. Relationships between tree density and bamboo clump density at the plot (n = 4) and subplot (n = 16) levels with prediction lines obtained from the Poisson generalized linear model (GLM) assuming that the area is 1 ha.

4.4. Discussion

4.4.1. Stand structure before the latest legal logging

Logging frequency is one of the most important parameters in yield regulation during selective logging in tropical natural forests. The MSS has a standard of a 30-year cutting cycle and the annual allowable cut is determined based on the assumption that the stocking of commercial trees has recovered 30 years after logging. Unfortunately, shorter cutting cycles were adopted because of the high demand for timber production in Myanmar, especially between 1990 and 2000 (Khai et al., 2016; Mon et al., 2012). Khai et al. (2016) revealed that a higher frequency of legal logging (five times in the last 18 years) can substantially reduce stocking; only 41 trees ha^{-1} and 8.25 m^2 ha^{-1} of BA remained prior to the latest legal logging. In contrast, this present study indicates that a compartment with a higher frequency of legal logging does not necessarily result in much lower levels of stocks. Rather, stocks (tree density and BA) in my plots were relatively similar to those in stands where no legal logging operations had occurred for several years (Khai et al., 2020b, 2016). These results call for a larger scale of forest inventory with systematic sampling in compartments to generalize the effects of logging frequency on stand structure. Win et al. (2018b) used data from 327 plots under systematic sampling with 2 km grids covering 139,360 ha in Bago Yoma, Myanmar, but their analysis focused on stand structure at the RF scale, but not at the compartment scale.

4.4.2. Legal and illegal logging

I found the amount of illegal logging during the 2 years after legal logging was much larger than legal logging (Figure 4.3). This result was consistent with that from Win et al. (2018d), who indicated that the number and BA of stumps resulting from illegal logging were 9.93- and 3.89-fold greater, respectively, than those of legal logging. The logistic GLM of this study indicated that illegal logging was targeted at species of higher quality for charcoal but not higher quality for timber. This is in contrast to Win et al. (2018d) and Khai et al. (2020a, 2016) who indicated that more illegal logging occurred for high-quality timber species such as teak and pyinkado. My study plots were within compartments where people had settled illegally, and Saung et al. (2020) indicated that such encroachers mostly engaged in charcoal making to generate income (see the photos 3 and 6 in the Supplementary Material S1). My GLM result on the preference for charcoal species for illegal logging is compatible with the survey results on charcoal making as a livelihood strategy (Saung et al., 2020). Moreover, I found charcoal kilns near the plots. Therefore, I can state that the illegally logged trees in my study sites were used mainly for charcoal making, which was conducted by encroachers. Illegal logging for timber focused mainly on a few very high-quality timber species, while my study revealed that illegal logging for charcoal targeted six to eight species in each plot and the amount of illegal logging is likely larger for charcoal making than for timber production (Khai et al., 2020b, 2016). Thus, illegal logging for charcoal making may be more destructive than that for timber production.

4.4.3. Stand structure after legal and illegal logging, and management implications

After legal and illegal logging, tree density and basal area were substantially reduced to 102 ± 57.6 trees ha^{-1} and 9.7 ± 1.4 m^2 ha^{-1} in mean ± SD (Table 4.1), although they were higher than in the study plot of Khai et al. (2016) where the values were only 20 trees ha^{-1} and 4.39 m^2 ha^{-1} for BA. These stocks are much lower than those in pre-logging conditions in the production forests in Myanmar (193 ± 58.9 and 16.85 ± 3.0 m^2 ha^{-1}) (Khai et al., 2020a), as well as in Central Africa (578 ± 42.4 tree ha^{-1}, 32.6 ± 3.9 m^2 ha^{-1}) (Gourlet-Fleury et al., 2013) and in Indonesia (530 ± 71.6 tree ha^{-1}, 31.5 ± 4.2 m^2 ha^{-1}) (Sist et al., 1998). These values are also lower than those reported for logged-over forests in other tropical regions; 25.2 m^2 ha^{-1} in East Kalimantan (Fadilah et al., 2003), 26.0 ± 6.4 and 24.1 ± 7.1 m^2 ha^{-1} in Sarawak, Malaysia (Kammesheidt et al., 2003), and 20.3 and 25.9 m^2 ha^{-1} in the Brazilian Amazon (J N M Silva et al., 1995). Species that had a high quality for timber but a low quality for charcoal, such as teak in plots 3 and 4 (Table 4.2, Figure 4.2), were almost untouched by illegal logging. Such stands may have future potential for timber production if illegal logging does not occur for a long time. However, species richness in my plots (18.3 ± 3.8 per 0.64-ha) may be smaller than that in pre-harvest stands in Myanmar (42.6 ± 6.7 per 1.0-ha) (Khai et al., 2020a), even though I cannot directly compare them due to differences in plot size.

Among the four plots, there was a wide range of tree density and bamboo clump density. My Poisson GLM model showed that there were negative relationships between tree density and bamboo clump density at the plot and subplot levels (Figure 4.5). This indicates that the lower the tree density, the higher the bamboo density. Studies show that bamboo dominance can reduce tree regeneration (Larpkern et al., 2009; Panadda et al., 2011) and control forest succession (Griscom and Ashton, 2003). In plot 2, which was the worst case in this study, tree density was only 32.8 trees ha^{-1}, while bamboo clump density was 145.3 clumps ha^{-1}. Such bamboo-dominated degraded forests may need active restoration such as assisted regeneration of commercial trees and bamboo cutting (Campanello et al., 2012; Philipson et al., 2020). To limit pioneer invasion and favor commercial species regeneration, it is necessary to limit logging intensity to an acceptable threshold, and 8 trees ha^{-1} of felling intensity or a 15% basal area reduction rate was recommended for a dipterocarp forest in Indonesia (Sist and Nguyen-the, 2002). In my present study, I cannot propose such a threshold due to lack of data on tree regeneration, but I can suggest that tree density should be maintained to at least 70 to 80 trees ha^{-1} because bamboo density sharply increased when tree density became less than these values (Figure 4.5).

When I consider restoration strategies in degraded forests in RFs, forest resource use by local people for their income should be taken into account, although the Myanmar forest law prohibits local households from harvesting forest products from RFs for commercial use without permission. Saung et al. (2020) revealed that many households living adjacent to RFs engage in illegal bamboo cutting to generate income. Thus, it may be an option to provide a legal right for local households to use bamboo resources sustainably, coupled with a strategy for restoring bamboo-dominated forests. In contrast, most of the encroachers in RFs were illegally engaged in charcoal making (Saung et al., 2020) and this present study has indicated that this illegal activity is a major factor of forest degradation. Because there is still an increasing demand for charcoal in rural areas in Myanmar (Win et al., 2018a), the establishment of a sustainable charcoal production system should be targeted through community forestry programs.

4.5. Conclusions

I found that compartments with a high frequency of legal logging did not necessarily show a heavily degraded condition. Rather, there was variation in terms of tree density and BA. A larger scale of forest inventory with systematic sampling is needed to generalize the effects of logging frequency on stand structure. In contrast, I confirmed that illegal logging following legal logging resulted in a substantial reduction in tree stocks. Illegally logged trees were used mainly for charcoal making by people who had settled illegally in the production forests. I also found that stands with lower tree density had higher bamboo density. Bamboo-dominated degraded forests need active restoration such as bamboo cutting and enrichment planting of commercial tree species. Legal participation from forest-dependent households may be effective both for the restoration of degraded forests and for the improvement of livelihoods.

Appendix II

Supplementary material Figure S1. Photographs of legal-and illegal-cut stumps and charcoal making

Photo 1. Hammer sign on legal stump in compartment 46

Photo 2. Legal-cut stump in compartment 46

Photo 3. Charcoal kiln in compartment 54

Photo 4. Illegal-cut stump of relatively small tree in compartment 46

Photo 5. Illegal-cut tree in compartment 46

Photo 6. Charcoal making in compartment 46

Supplementary Material Table S2

The result of the Poisson GLM for bamboo clump counts (number per the surveyed area) with log of surveyed area (ha) as the offset, in relation to tree density (number ha-1) for data from the plots (n = 4, each surveyed area = 0.64 ha) and subplots (n = 16, each surveyed area = 0.16 ha).

Data sources	Variable	Estimate	SE	z-value	Pr(>|z|)
Plot (n=4)					
	Intercept	5.6518	0.1587	35.6070	<0.0001
	tree density	-0.0225	0.0026	-8.6930	<0.0001
Subplot (n=16)					
	Intercept	5.4317	0.1483	36.6170	<0.0001
	tree density	-0.0203	0.0024	-8.2870	<0.0001

Chapter 5

Stand dynamics and interactions among adult trees, bamboo and tree regeneration in illegally logged production forests in Myanmar

5.1. Introduction

There is increasing attention on restoring degraded forests in the tropics because forest degradation is a major contributor to carbon emissions and biodiversity loss (Budiharta et al., 2014; Lamb et al., 2005; Philipson et al., 2020). In many countries, the areas affected by forest degradation exceed those affected by deforestation (Pearson et al., 2017). For example, a recent study revealed that forest degradation surpassed deforestation in the entire Brazilian Amazon over the past two decades (Matricardi et al., 2020). Forest degradation is often associated with a reduction in forest biomass (Budiharta et al., 2014; Sasaki and Putz, 2009), which is largely induced by the decrease in large canopy trees (Sist et al., 2014). A reduced number of canopy trees can result in more abundant understory vegetation such as grasses and shrubs, and, in turn, the understory abundance can affect tree regeneration either positively or negatively (Tálamo et al., 2020). Thus, when I assess restoration activities for degraded forests, it is essential to understand the interactions among the three components of canopy trees, understory vegetation and tree regeneration. However, there have been limited studies quantifying the overall relationships among the three components (Redmond et al., 2018; Wallace et al., 2017).

Bamboo is an important structural component of many tropical forest ecosystems (Bona et al., 2020). Bamboo dominance is generally associated with lower tree density (Fadrique et al., 2021). Many studies have shown that bamboo can hamper tree regeneration through its competitive superiority in terms of the capture of light and other resources (Fadrique et al., 2021; Larpkern et al., 2011). However, I still lack quantitative information on the overall interactions among canopy trees, bamboo and tree regeneration, since bamboo is commonly excluded from forest monitoring and modelling (Fadrique et al., 2021).

Forest degradation has been often found in selectively logged production forests in the tropics (Asner et al., 2006; Pearson et al., 2014). The main reasons are over-harvesting and substantial damage to residual stands during logging operations (Sasaki and Putz, 2009). Since selectively logged forests have conservation values in terms of various ecosystem services (Edwards et al., 2014; Putz et al., 2012), ways of improving forest management through reduced-impact logging (Putz et al., 2008) and restoring logged forests (Cerullo and Edwards, 2019) are receiving global attention. The research group of Kyushu University, Japan, has focused on forest degradation issues in selectively logged natural production forests in Myanmar. Myanmar has a long tradition of applying the Myanmar Selection System (MSS) using elephants for skidding, and the MSS is considered an example of good practice in tropical forestry. However, remote sensing (Mon et al., 2012, 2010) and field inventories with systematic sampling (Win et al., 2018b) have revealed large scale forest degradation in these production forests. Win et al. (2018b) also investigated legal and illegal stumps, revealing that the amount of illegal logging was much larger than that of legal logging over the preceding 10 years, and that illegal logging was facilitated by legal logging operations which provided better access to forests through the construction of logging roads. Illegal logging first targets large and high-quality timber species such as teak (*Tectona grandis*) and pyinkado (*Xylia xylocarpa*) (Khai et al., 2020b, 2016). After repeated legal and illegal logging had resulted in a shortage of timber species, illegal logging targets various species and tree sizes for charcoal making (Khai et al., 2016; Saung et al., 2021). Saung et al. (2021) found that stands with lower tree density had more bamboo in illegally logged stands in compartments that were subject to inappropriately short rotations of legal logging. Based on these findings, I developed a working hypothesis that illegal logging, coupled with high frequency legal logging, is a major reason for forest degradation, and reduced tree density may negatively impact on tree regeneration by increasing the dominance of bamboo.

This present study was based on two surveys between 2 and 7 years after legal logging last occurred at four plots established by (Saung et al., 2021). I first aimed to measure the 5-year changes in stand structure (increment, recruitment, mortality, regeneration, illegal logging and bamboo stocks). Second, I used structural equation modeling (SEM) to confirm the interactions among adult trees, bamboo and tree regeneration and to discuss the implications for forest management.

5.2. Materials and Methods

5.2.1. Study area

This study was based on two sets of measurements in four sample plots that were established in 2013 (Saung et al., 2021). The study plots are located in South Zamaye Reserved Forest (RF), Bago Township, the southeastern part of Bago Yoma, Myanmar (Figure 5.1). The dominant forest type in the RF is a moist upper mixed deciduous forest where teak, pyinkado, and other commercial species can be found with bamboo species (*Bambusa polymorpha* and *Cephalostachyum pergracile*), which usually form large clumps. Detailed information on the study sites can be found in (Saung et al., 2021).

Four plots were established in three compartments where legal logging operations were last conducted in 2011 and the frequency of official logging had been higher than the MSS standard 30-year rotation cycle (e.g., logging occurred once every 30 years). Under the MSS, trees to be harvested are marked by the Myanmar Forest Department based on the prescribed species and prescribed minimum diameter cut limit (MDCL), and then the Myanmar Timber Enterprise and/or its subcontracting agent perform the logging operations including tree felling, log stumping and skidding, logging road construction, and log transportation, normally in July through December. Forest roads for log transportation are constructed at the end of the rainy season, after November when the soil hardens.

The MDCL varies depending on the species. For teak, Dipterocarpus spp., *Hopea odorata*, *Anisoptera scaphula* and *Parashorea stellata*, the minimum exploitable diameter at breast height (DBH) is 78 cm. The MDCL for pyinkado, *Lagerstroemia speciosa* and *Lagerstroemia tomentosa* is prescribed at 68 cm, whereas other hardwood species are set at 58 cm. Tree species are classified into six commercial species groups; teak, and Groups I–V, depending on the commercial value. Teak represents the most valuable, and the commercial value as timber decreases from Group I through V. Pyinkado, *Pentacme siamensis* and *Dalbergia oliveri* are the representative species of Group I, and Group V has lesser-used species (LUS). While selecting and cutting the trees with the minimum exploitable limits, Myanmar Forest Department and Myanmar Timber Enterprise staff put their hammer marks on the remaining stumps and cut logs to ensure the legality of logging operations. Hammer-marked information on the stump surface includes tree number, log number from the single tree, and the code of a person in charge.

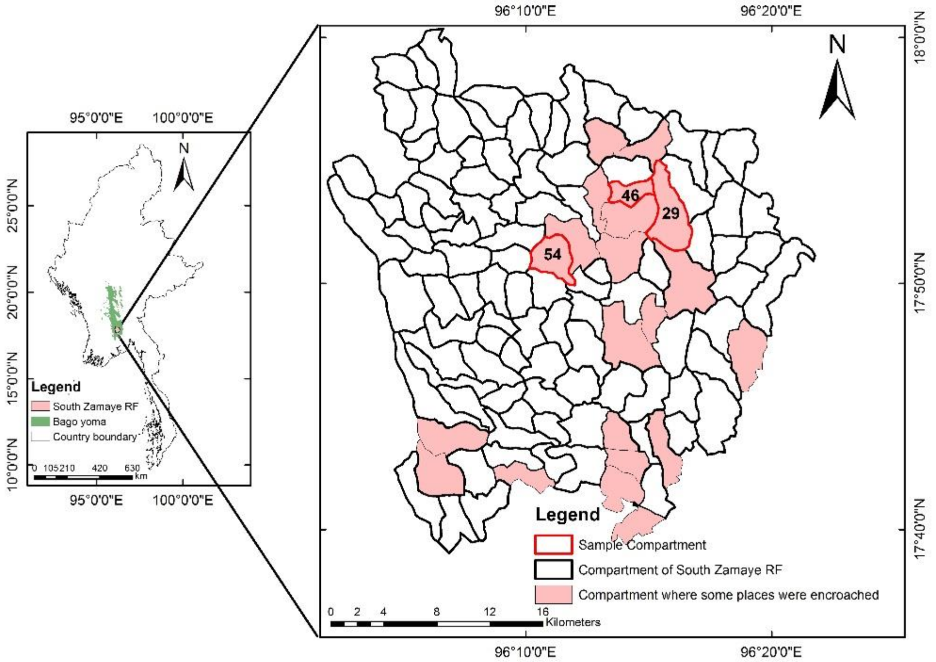

Figure 5.1. Location of study sites in South Zamaye RF, Bago Township, Myanmar.

5.2.2. Field measurements and data preparation

Data were collected twice, in December 2013 and December 2018. In December 2013, four permanent sample plots (80 m × 80 m) were set up; one plot in compartments 29 and 54 and two in compartment 46 (Figure 5.1). To establish the sample plots, a starting point was selected to include legally logged stumps and/or illegally logged ones. Then, the base line and diagonal lines were set in north to south and east to west directions from this starting point. Each plot was divided into 16 subplots (20 m × 20 m). In each plot, all standing trees ≥ 10 cm diameter at breast height (DBH) were tagged, identified and their DBHs were measured. All the bamboos were recorded as number of culms in the *i*th bamboo clump (n_i), and the maximum and minimum culm diameter ($D_{i,max}$ and $D_{i,min}$). The basal area of the *i*th bamboo clump (BA_i) was calculated (Thein et al., 2007) as:

$$BA_i = n_i \times D_{i,max} \times D_{i,max} \times \frac{\pi}{4000}, \quad (1)$$

All recorded trees and bamboos with a local name were then confirmed using the checklist of Kress and Lace (2003).

In December 2018, I visited the plots to check whether the trees that had been measured in 2013 were living, naturally dead or illegally cut, and I re-measured the DBH of living trees. I also measured the DBH and identified the species of newly recruited trees, where the DBH was equal to or more than 10 cm in 2018. Bamboo was also measured in 2018.

In each subplot (20 m × 20 m) within the four plots (n = 64), a circular plot with a 5 m radius (78.5 m^2) was set up at the center, and naturally regenerated trees, which were defined in this study as trees with DBH ≤ 10 cm and tree height ≥ 1.3 m, were recorded for species, DBH, and tree height.

5.2.3 Data analysis

First, I summarized the statistics of changes in stand structure (mortality, illegal cut, recruitment, regeneration) and in bamboo stocks between 2013 and 2018, for each subplot and plot. The annual mortality and recruitment rates were estimated using the following equation (Sist and Nguyen-the, 2002):

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

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; and, 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 and Nguyen-the, 2002). Among 316 living trees in 2018, three trees had differences in DBH measurements of more than 20 cm between 2013 and 2018. This abnormal difference may be due to the effects of lianas or measurement errors, and I corrected the DBH in 2018 of these trees to be the same as that in 2013.

Second, I applied structural equation models (SEM) to identify interactions among adult trees (DBH ≥ 10 cm) in 2013, bamboo, and regenerated trees (DBH ≤ 10 cm, tree height ≥ 1.3 m) at the subplot level (n = 64), using the piecewise SEM package (Lefcheck, 2016). Structural equation models are probabilistic models that unite multiple predictor and response variables in one integrated casual framework, and they are represented using path diagrams, where arrows indicate the directional relationships between variables (Lefcheck, 2016). My SEM was constructed based on my hypothesis that adult tree density affects bamboo stocks, and in turn, bamboo stocks affect tree regeneration. As a measure of tree density, I used the number of trees (DBH ≥10 cm) in 2013 since my preliminary analysis showed the total basal area of trees had a weaker relationship with bamboo abundance in 2018 than did the number of trees. As a measure of bamboo stocks in 2018, I tested three variables: the number of clumps, the number of culms and the total basal area of culms. These three measures of bamboo were significantly correlated with each other, and thus, they were excluded from the basis set and treated as correlated errors (Lefcheck, 2016). To account for the non-normality of data, I applied a generalized linear model (GLM) with “Poisson” family with log link for the response variables of count data. For total basal area, which is a continuous variable with zero and positive values, I applied a linear model (LM) using data with a square-root transformation. I did not include random effect terms for site or experimental pairs of trees since these did not significantly contribute to model fit. Shipley’s test of d-separation (Shipley, 2009) was used to test the model fit of my SEM.

The SEM could not calculate standardized coefficients for the GLM with Poisson distribution. Following the procedures adopted by (Fadrique et al., 2021), I constructed another SEM for the same relationships using linear models with transformed data. All variables were square-root-transformed rather than the more commonly use log-transformed, since most of the variables included zero.

5.3. Results

5.3.1. Changes in stand structure between 2 and 7 years after legal logging

In the 5 years between 2 and 7 years after legal logging, the net changes in tree stocks were smaller than those of bamboo (Table 5.1). Tree density increased by 21% from 102 to 123 trees ha^{-1} while total basal area decreased by 12% from 9.7 to 8.5 m^2 ha^{-1} on average for the four plots. In contrast, the number of bamboo clumps increased rapidly by 267% from 56 to 205 clumps ha^{-1}; the number of culms increased by 316% from 809 to 3368 clumps ha^{-1}; and the total basal area increased by 129% from 3.5 to 7.9 m^2 ha. At the subplot level (n = 64), bamboo stocks in 2018 were negatively related to the number of trees in 2013, and the increase in bamboo stocks from 2013 to 2018 was larger than the increase in tree density (Figure 5.2 and Table S1).

The net increase in tree numbers was relatively large in the smallest DBH classes (10 to 20 cm) for all the plots (Figure S1), and the annual recruitment rate was

9.6% on average, ranging from 6.7% to 13.5% (Table 5.1). Natural mortality was 2.9% on average (range 0.0%–4.4%) and occurred in various DBH classes except for plot 2 (Figure 5.3). Illegal logging was 14.5 trees ha^{-1} on average, but it was found mainly in plots 3 and 4 in the various DBH classes, while only a few trees ha^{-1} were illegally cut in the other plots (Table 5.1, Figure 5.3). In three plots (excluding plot 1), the reduction in basal area because of illegal logging was more than the increase from the increment of living trees in both 2013 and 2018 and from recruitment (Figure 5.4).

Tree species richness increased from 48 to 58 for all the plots. The composition of the commercial species groups for each plot (relative share of tree numbers) was similar between 2013 and 2018 (Figure S1 and Table S2). Group IV species were the most dominant for all the plots in 2018, and teak was relatively dominant in plots 3 and 4 (Figure S1 and Table S2).

The number of regenerated trees (DBH ≤ 10 cm, tree height ≥ 1.3 m) in 2018 was 2,001 trees ha^{-1} on average, ranging from 1,066 in plot 2 to 3,740 in plot 3. Among the commercial species groups, groups II and IV were relatively dominant, and teak was found only in plots 3 and 4 (Table S2). At the subplot level (n = 64), the number of regenerated trees was negatively related to bamboo stocks (number and basal area of culms, and number of clumps) (Figure 5.5 and Table S3)**.**

Table 5.1. Changes in stand structure for trees (DBH >10 cm) and bamboo from 2013 to 2018, and regenerated trees (DBH < 10cm, tree height > 1.3 m) in 2018 in the four plots.

Attributes	Plot 1	Plot 2	Plot 3	Plot 4	Mean
Stand structure in 2013					
Tree density (trees ha^{-1})	64.1	32.8	181.3	129.7	102.0
Mean tree DBH (cm)	38.6	45.1	24.4	29.9	34.5
Tree BA (m^2 ha^{-1})	9.5	7.6	10.1	11.4	9.7
Tree species richness (counts 0.64-ha^{-1})	15	14	22	23	48
Bamboo clump density (clumps ha^{-1})	54.7	145.3	6.3	17.2	55.9
Bamboo culm density (culms ha^{-1})	928	1834	178	297	809
Bamboo clump BA (m^2 ha^{-1})	4.42	7.89	0.47	1.08	3.5
Illegal cut trees from 2013 to 2018					
Cut-tree number (trees ha^{-1})	1.56	3.13	20.3	32.8	14.5
Mean cut-tree DBH (cm)	18.2	67.0	39.5	34.8	39.9
Cut-tree BA (m^2 ha^{-1})	0.04	1.10	3.49	4.11	2.2
Cut-tree species number (counts 0.64-ha^{-1})	1	1	6	12	14
Mortality of trees from 2013 to 2018					
Tree number (trees ha^{-1})	14.1	0.00	31.3	14.1	14.8
Annual mortality rate (%)	4.4	0.0	3.4	2.2	2.9
Mean tree DBH (cm)	37.7	0.00	22.7	30.8	22.8
Tree BA (m^2 ha^{-1})	1.94	0.00	1.40	1.45	1.2
Tree species number (counts 0.64-ha^{-1})	3	0	10	6	17
Recruitment from 2013 to 2018					
Tree number (trees ha^{-1})	26.6	10.9	70.3	87.5	48.8
Annual recruitment rate (%)	8.3	6.7	7.8	13.5	9.6
Mean tree DBH (cm)	32.2	37.0	21.1	22.1	28.1
Tree BA (m^2 ha^{-1})	0.40	0.21	0.95	1.18	0.7
Tree species number (counts 0.64-ha^{-1})	10	6	17	17	39
BA Increment of trees living from 2013 to 2018 (m^2 ha^{-1})	1.07	0.63	2.31	1.97	1.5
Stand structure in 2018					
Tree density (trees ha^{-1})	78.1	40.6	201.6	173.4	123.4
Mean tree DBH (cm)	32.2	37.0	21.1	22.1	28.1
Tree BA (m^2 ha^{-1})	9.01	7.37	8.51	8.98	8.5
Tree species richness (counts 0.64-ha^{-1})	23	19	23	26	58
Bamboo clump density (clumps ha^{-1})	319	328	127	47	205
Bamboo culm density (culms ha^{-1})	4883	5875	1853	863	3368
Bamboo clump BA (m^2 ha^{-1})	9.76	17.5	2.59	1.95	7.9
Tree regeneration (DBH < 10cm, tree height > 1.3m)					
Density (trees ha^{-1})	1098	1066	3740	2101	2001
Species richness (counts 0.126-ha^{-1})	28	31	26	26	61

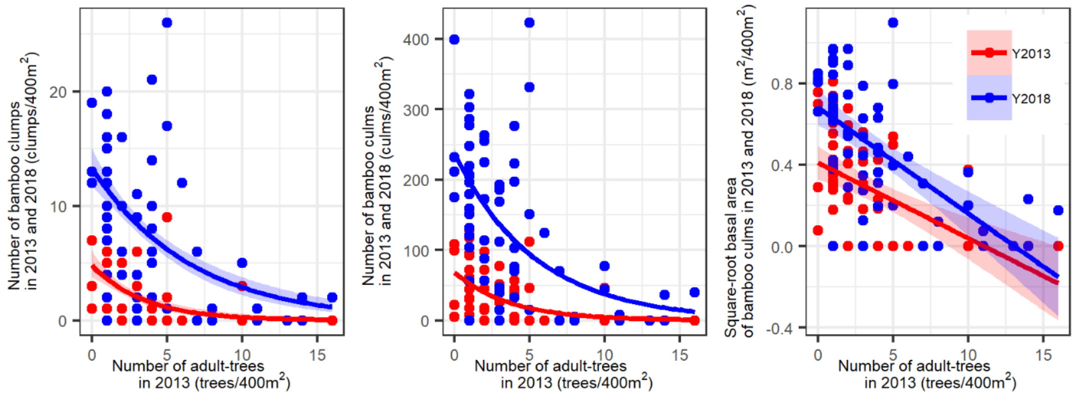

Figure 5.2. Relationships between bamboo stocks (number of clumps and culms and basal area of culms) in 2013 and 2018 and number of trees in 2018 at the 400 m^2 subplots (n = 64).

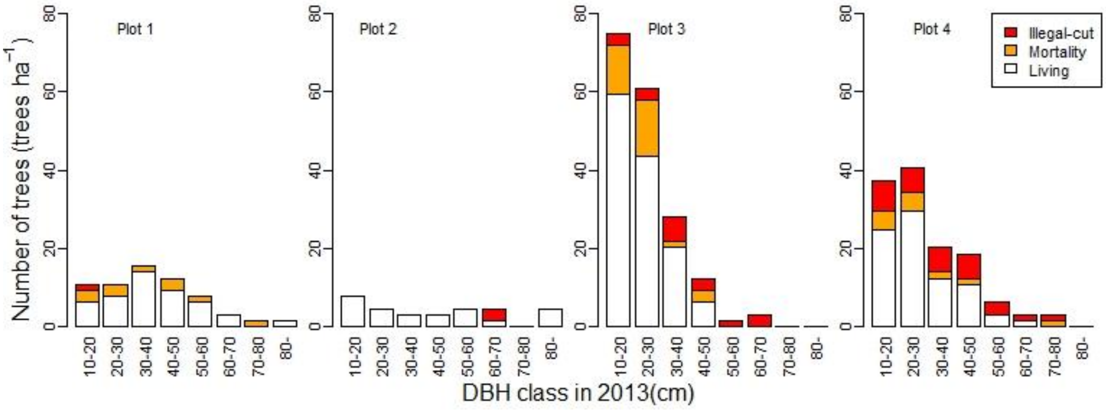

Figure 5.3. The DBH distribution in 2013 with status between 2013 and 2018 (living, illegally-cut or natural mortality).

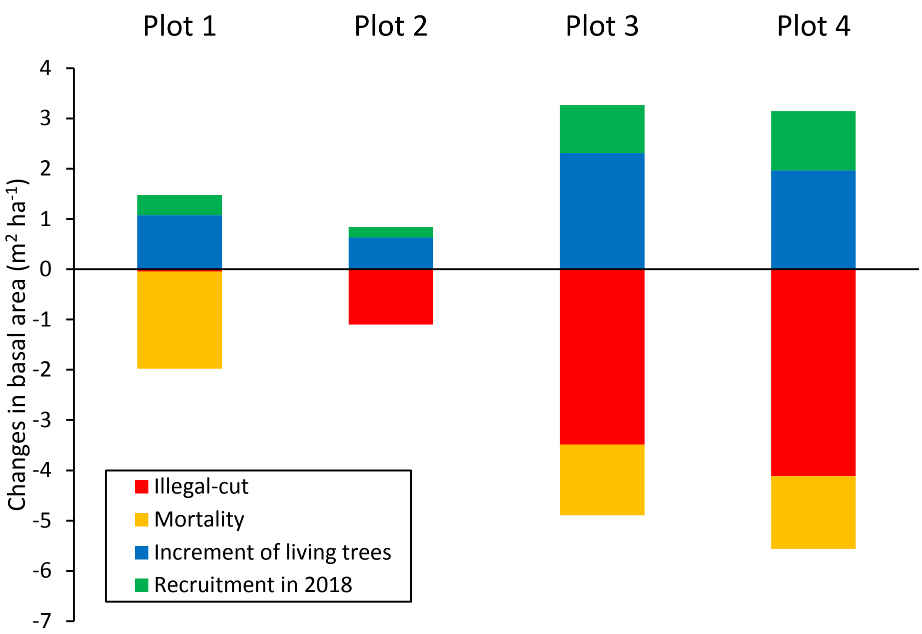

Figure 5.4. Changes in basal area (m^2 ha^{-1}) for each component between 2013 and 2018.

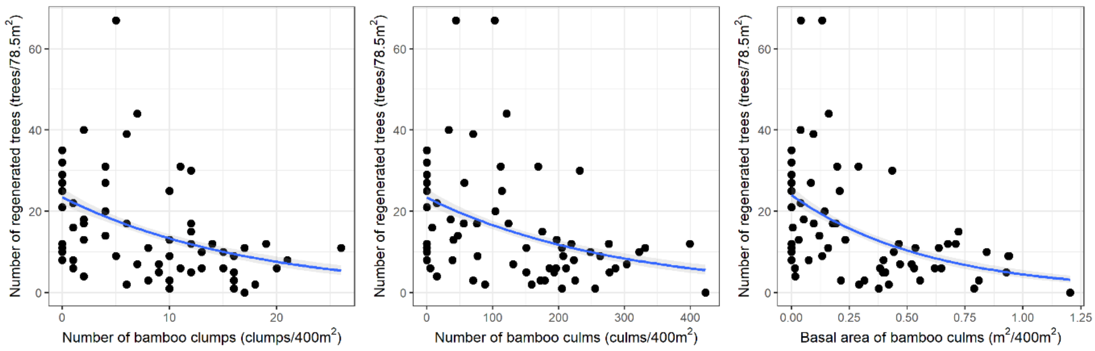

Figure 5.5. Relationships between the number of regenerated trees in the 78.5 m^2 circular plots and bamboo stocks (number of clumps and culms, and basal area of culms) in the 400 m^2 subplots.

5.3.2. Structural equation model among adult trees, bamboo and tree regeneration

My SEM (Figure 6 and Table S4) adequately fitted the data (Fisher's C = 3.672, p = 0.159), since $p > 0.05$ indicates no significant lack of fit between the model and the data (Fadrique et al., 2021). A second SEM that used a square-root-transformed data set also fitted the data well (Fisher's C = 1.369, p = 0.504) (Table S5). The results indicated that the number of trees had a direct negative association with all the three measures of bamboo stocks, where the standardized coefficients were similar. The basal area of bamboo culms had a direct negative association with the number of regenerated trees. The standardized coefficients indicated an overall positive relationship between the number of adult trees and number of regenerated trees through a reduction in the basal area of bamboo culms (−0.67 × −0.97 = 0.65).

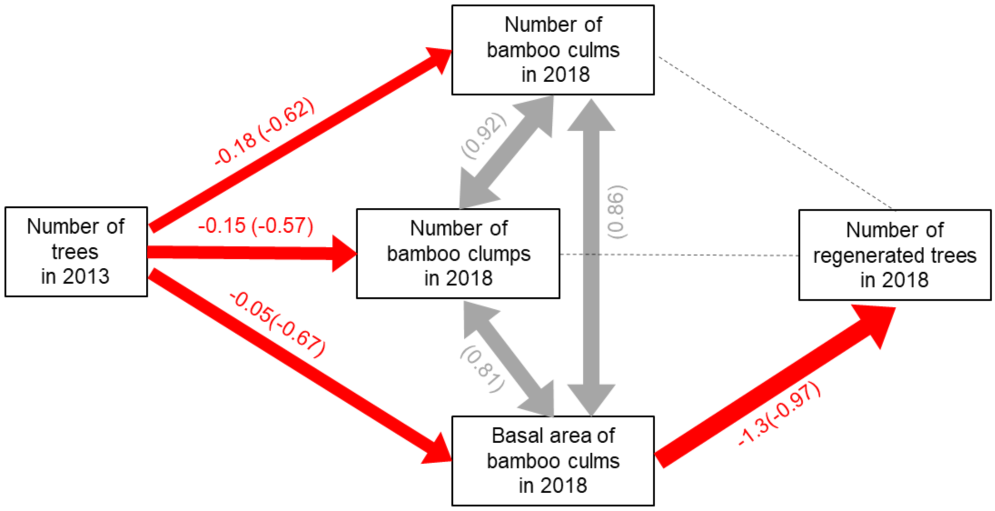

Figure 5.6. Structural equation model (SEM) for the number of regenerated trees. Line thickness is proportional to the standardized coefficients that are shown in parentheses while unstandardized coefficients are shown outside the parentheses. One-headed red arrows represent a negative causal effect of one variable on another. Double-headed grey arrows link variables with correlated errors.

5.4. Discussion

5.4.1. Continued illegal logging

There have been many studies on post-harvest stand dynamics in tropical forests (Finegan and Camacho, 1999; Schulze and Zweede, 2006; J. N.M. Silva et al., 1995), but few studies have examined the incidence and impacts of illegal logging over time (Khai et al., 2020b; Win et al., 2018d). I found that illegal logging continued in the 5-year period between 2 and 7 years after legal logging, although the average amount of illegal logging (14.5 trees ha^{-1}, 1.9 m^{2} ha^{-1}) was reduced in comparison with levels in the 2 years immediately after legal logging (27.3 trees ha^{-1}, 5.6 m^{2} ha^{-1}) (Saung et al., 2021). A similar amount of illegal logging (13.4 trees ha^{-1}, 3.0 m^{2} ha^{-1}) was found in larger-scale systematic sampling of illegal stumps following illegal logging in the preceding 10 years in the production forests in Myanmar (Win et al., 2018d). Among my four plots, the two plots with higher stocks still had substantial levels of illegal logging while the other two plots with lower stocks had less (Figure 5.3). It can be stated that illegal logging is likely to be high for a few years after legal logging and then decline over time as remaining stocks of commercial trees are reduced.

5.4.2. Stand dynamics for trees with DBH ≥ 10 cm

The mortality, recruitment and increment of living trees are the basic components of stand dynamics (Gerald E. Lang and Dennis H. Knight, 1983; Marín et al., 2005; Rozendaal and Chazdon, 2015). The average mortality rate (2.9%) in the present study was similar to the reported values for selectively logged forests, but larger than those unlogged forests. For example, studies showed the mortality rate was 2.5% more than 5 years after logging (Khai et al., 2020b) and 3.2% more than 7 years after logging (Dionisio et al., 2018). In general, the mortality rates ranged between 1% and 2% in unlogged natural tropical forests (M . D . Swaine. et al., 1987), and tended to decrease over time after timber harvesting, such as rates of 2.6%, 2.4%, and 2.2% after 5, 6, and 11 years, respectively, in the Brazilian Amazon (J N M Silva et al., 1995). The relatively high mortality rate in this study may be because of continuous illegal logging for the 7 years since the latest official logging rotation in 2011. However, repeated illegal logging following inappropriately short rotations of legal logging in my study sites most likely contributed to the relatively high growth of the remaining trees. The annual recruitment rate of 9.6% was much higher than the reported values in other tropical forests: 2.3% ± 0.13% (n = 32) and 1.8% ± 0.7% (n = 9) for mature rain forests in the Amazon Basin (Phillips et al., 2004) and Southeast Asia (Unless et al., 1994), respectively. Khai et al. (2020a) found a recruitment rate of 3.1% for the 5 years post-harvest in less disturbed stands in Myanmar, which were subject to one-time legal logging over 17 years between 1995 and 2012. The annual DBH increment rate of living trees (0.58 ± 0.47 cm $year^{-1}$) was also larger than previous values reported in Myanmar of 0.48 cm $year^{-1}$ in the less disturbed stands (Khai et al., 2020b) (t-test, $p = 0.0043$) and 0.32 cm $year^{-1}$, which has been used traditionally to calculate the sustainable yield for the 30-year cutting cycle under the MSS (t-test, $p < 0.0001$). Better growth of the remaining trees in this study may be induced by the relatively large disturbance with continued illegal logging following repeated legal logging. This is compatible with the findings from a long-term monitoring study that the increasing intensity of logging results in more recruitment and larger DBH growth (Amaral et al., 2019).

In terms of the change in total basal area, the increase from the recruited and living trees was more than or nearly balanced by the loss from mortality (Figure 5.4).

However, I found that illegal logging was the major contributor of net negative changes in basal area in all the plots except plot 1 where only one small tree was illegally cut (Figures 5.3 and 5.4).

5.4.3. Interactions among adult trees, bamboo and tree regeneration

Bamboo is widely distributed in tropical forests, and it can be dominant in degraded forests (Panadda et al., 2011). However, there has been a dearth of quantitative data on changes in bamboo abundance over time. My study has revealed that bamboo substantially increased over the 5 years from 2013 and 2018 (Table 5.1). I also found that bamboo stocks were generally larger under conditions of less tree density, and the increases in bamboo stocks were also larger in plots with lower tree density (Figure 5.2). This result confirmed that bamboo became more dominant over time in more degraded forests with lower tree stocks. Securing sufficient regeneration of commercial timber species after selective logging is crucial for sustainable tropical forest management (Fredericksen and Pariona, 2002). Studies have observed that bamboo dominance can reduce tree regeneration (Larpkern et al., 2011, 2009) and control forest succession (Griscom and Ashton, 2003). My study also confirmed that tree regeneration was reduced with increasing bamboo stocks (Figure 5.2).

My SEM showed that there was a negative direct association between tree density and all three measures of bamboo stocks: number and basal area of culms, and number of clumps, while a negative association was found between bamboo basal area and the number of regenerated trees (Figure 5.6). This result indicates that reduced adult tree density indirectly caused less tree regeneration by increasing bamboo basal area. Such direct and indirect relationships among adult trees, understory vegetation and tree regeneration were found in the dry forests of Argentina (Tálamo et al., 2020), temperate rainforest of New Zealand (Wallace et al., 2017) and pinyon pine-juniper forests of the southwestern USA (Redmond et al., 2018), where shrub basal area, exotic weeds, and both shrubs and weeds were taken into account as understory vegetation, respectively. In these cases, controlling understory vegetation is important to promote tree regeneration. In my case, bamboo cutting may be needed to ensure tree regeneration in bamboo-dominated, and degraded stands (Campanello et al., 2012; Philipson et al., 2020). Since the basal area of bamboo had a more significant negative impact on tree regeneration rather than number of clumps or culms (Figure 5.6), the cutting of larger culms may be an effective management action. Bamboo is an important non-timber forest product for cash income for local households living around the RFs in Myanmar, even though the Myanmar forest law prohibits local households from harvesting forest products from RFs for commercial use without permission (Saung et al., 2020). Thus, bamboo cutting may be an effective measure in the long-run, providing a legal right for local households to use bamboo resources sustainably, coupled with a strategy for restoring bamboo-dominated forests.

5.4.4. Study limitations

One of my study limitations is the small sample size (n = 64 in four plots), so that statistical modeling was applied using all the data, which meant the species data were pooled. In terms of silvicultural objectives, it would be useful to carry out analysis for each of the commercial species groups and/or individual species as done by (Tálamo et al., 2020). In addition, I may need to divide the data into different functional groups, such as shade-tolerant and -intolerant species. However, I lack information on functional types of each species found in the production forests of Myanmar. Further research with more sample plots is needed to consider functional species characteristics.

5.5. Conclusions

Studies on post-harvest stand dynamics lack information on subsequent illegal logging and overall interactions among trees, understory vegetation and tree regeneration. I found that illegal logging continued for 7 years following repeated legal logging under short rotation in the production forests of Myanmar. Repeated illegal logging was a major contributor to decreasing the total basal area of plots. Such a repeated disturbance resulted in a substantial increase of bamboo stocks. Bamboo stocks were larger in stands with a lower density of trees (DBH > 10 cm), and in turn, tree regeneration (DBH < 10 cm) was lower in stands with more bamboo stocks. I conclude that reduced tree density owing to repeated legal and illegal logging indirectly caused less tree regeneration by increasing bamboo stocks. Providing a legal right to forest-dependent households to harvest bamboo as a non-timber forest product to generate income, coupled with controlling illegal logging, may be an effective way to restore bamboo-dominated, degraded production forests as well as to improve local livelihoods.

Appendix III

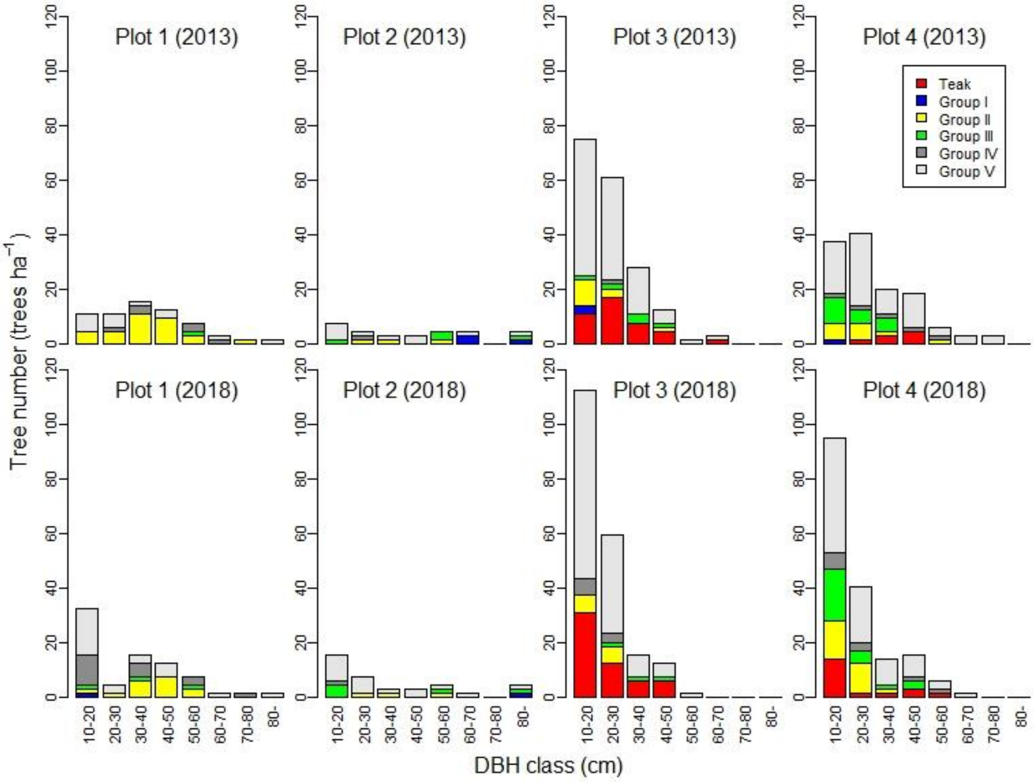

Figure S1. The DBH distribution in 2013 and 2018 for each commercial species group.

Table S1. Generalized linear model (GLM) and LM results of relationships between bamboo stocks in 2013 and 2018 and the number of adult trees in 2013.

Response	Predictor	Estimate	Std. Error	z or t value	Pr(>|z|) or Pr(>|t|)	AIC
Number of bamboo clumps in 2013	Number of trees in 2013	-0.28464	0.04473	-6.363	<0.0001	272.08
Number of bamboo clumps in 2018	Number of trees in 2013	-0.15222	0.01709	-8.908	<0.0002	499.32
Number of bamboo culms in 2013	Number of trees in 2013	-0.26954	0.01138	-23.68	<0.0001	2401.7
Number of bamboo culms in 2018	Number of trees in 2013	-0.184012	0.004573	-40.23	<0.0001	4749.4
Square-rooted basal area of bamboo culms in 2013	Number of trees in 2013	-0.037095	0.007419	-5.000	<0.0001	-3.3691
Square-rooted basal area of bamboo culms in 2018	Number of trees in 2013	-0.05204	0.007837	-6.641	<0.0001	3.6452

Table S2. Changes in tree density (ha^{-1}) from 2013 and 2018 for each commercial species group.

Species group	Stand in 2013				Illegally cut trees				Mortality				Recruitement				Stand in 2018				Regeneration in 2018			
	Plot 1	Plot 2	Plot 3	Plot 4	Plot 1	Plot 2	Plot 3	Plot 4	Plot 1	Plot 2	Plot 3	Plot 4	Plot 1	Plot 2	Plot 3	Plot 4	Plot 1	Plot 2	Plot 3	Plot 4	Plot 1	Plot 2	Plot 3	Plot 4
Teak	0.0	0.0	42.2	9.4	0.0	0.0	3.1	3.1	0.0	0.0	7.8	0.0	0.0	0.0	25.0	15.6	0.0	0.0	56.3	21.9	0	0	350	183
Group I	0.0	4.7	3.1	1.6	0.0	3.1	0.0	1.6	0.0	0.0	3.1	0.0	1.6	0.0	0.0	0.0	1.6	1.6	0.0	0.0	24	191	40	72
Group II	32.8	4.7	14.1	15.6	1.6	0.0	1.6	1.6	12.5	0.0	1.6	0.0	1.6	0.0	1.6	12.5	20.3	4.7	12.5	26.6	454	342	724	645
Group III	1.6	4.7	7.8	18.8	0.0	0.0	1.6	6.3	0.0	0.0	1.6	0.0	1.6	3.1	0.0	15.6	4.7	7.8	4.7	28.1	64	56	48	16
Group IV	9.4	0.0	1.6	6.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.9	1.6	7.8	6.3	20.3	1.6	9.4	12.5	48	40	0	72
Group V	20.3	18.8	112.5	78.1	0.0	0.0	14.1	20.3	1.6	0.0	17.2	14.1	10.9	6.3	35.9	37.5	31.3	25.0	118.8	84.4	509	438	2578	1114
Total	64.1	32.8	181.3	129.7	1.6	3.1	20.3	32.8	14.1	0.0	31.3	14.1	26.6	10.9	70.3	87.5	78.1	40.6	201.6	173.4	1098	1066	3740	2101

Table S3. GLM results of the relationships between the number of regenerated trees and bamboo stocks.

Response	Predictor	Estimate	Std. Error	z value	Pr(>|z|)	AIC
Number of regenerated trees	Number of bamboo clumps	-0.05659	0.005396	-10.49	<0.0001	838.3
Number of regenerated trees	Number of bamboo culms	-0.003422	0.0003247	-10.54	<0.0001	836.12
Number of regenerated trees	Basal area of bamboo culms	-1.6829	0.13449	-12.51	<0.0001	768.23

Table S4. Structural equation model (SEM) results from applying the GLM and LM to untransformed data, except for the basal area of bamboo culms.

Response	Predictor	Estimate	Std. Error	DF	P.Value	Std.Estimate
Number of bamboo clumps in 2018	Number of trees in 2013	-0.1522	0.0171	62	0.000	-
Number of bamboo culm in 2018	Number of trees in 2013	-0.184	0.0046	62	0.000	-
Square-root of basal area of bamboo culms in 2018	Number of trees in 2013	-0.052	0.0078	62	0.000	-0.6447
Square-root of basal area of bamboo culms in 2018	Number of bamboo clumps in 2018	0.7624	-	64	0.000	0.7624
Square-root of basal area of bamboo culms in 2018	Number of bamboo culm in 2018	0.8531	-	64	0.000	0.8531
Number of bamboo clumps in 2018	Number of bamboo culm in 2018	0.8959	-	64	0.000	0.8959
Number of regenerated trees in 2018	Number of bamboo clumps in 2018	-0.0153	0.012	60	0.202	-
Number of regenerated trees in 2018	Square-root of basal area of bamboo culms in 2018	-1.3044	0.2602	60	0.000	-
Number of regenerated trees in 2018	Number of bamboo culm in 2018	0.001	9.00E-04	60	0.269	-

Table S5. SEM results applying the LM to the square-root transformed data set.

Response	Predictor	Estimate	Std. Error	DF	P.Value	Std.Estimate
Square-root of number of bamboo clumps in 2018	Square-root of number of trees in 2013	-0.8636	0.1587	62	0.000	-0.5687
Square-root of number of bamboo culm in 2018	Square-root of number of trees in 2013	-3.9182	0.6194	62	0.000	-0.6263
Square-root of basal area of bamboo culms in 2018	Square-root of number of trees in 2013	-0.2195	0.0312	62	0.000	-0.6666
Square-root of basal area of bamboo culms in 2018	Square-root of number of bamboo clumps in 2018	0.8146	-	64	0.000	0.8146
Square-root of basal area of bamboo culms in 2018	Square-root of number of bamboo culm in 2018	0.8851	-	64	0.000	0.8851
Square-root of number of bamboo clumps in 2018	Square-root of number of bamboo culm in 2018	0.9221	-	64	0.000	0.9221
Square-root of number of regenerated trees in 2018	Square-root of number of bamboo clumps in 2018	-0.2566	0.3921	60	0.515	-0.2233
Square-root of number of regenerated trees in 2018	Square-root of basal area of bamboo culms in 2018	-5.1419	1.5942	60	0.002	-0.9704
Square-root of number of regenerated trees in 2018	Square-root of number of bamboo culm in 2018	0.2000	1.25E-01	60	0.116	0.7172

Chapter 6

General Conclusion and Recommendations

Global concern is growing towards sustainable management of tropical production for timber and non-timber products, and ecosystem services as well. Accordingly, more global attention paid on improving logging practices in reducing remaining stand damage and restoration of degraded tropical production forests. Human disturbances co-occurring with selective logging is highlighted as current global threat to tropical forests. Understanding the nature of human disturbances and the condition of degraded forests seems to be of important in developing effective restoration strategies. However, there was limited observations conducted in illegally logged production forests, considering local people's dependence on nearby production forests. This study observed local people's forest use strategies and dependence level for cash income on nearby selectively logged forests, and stand dynamics of illegally logged production forests using time series data over five years. The study was conducted in Bago Township, the southeastern part of Bago Yoma, Myanmar, where timber harvesting, using Myanmar Selection System (MSS), has been conducted since 1856, and 10 year logging ban has launched since 2016.

Regarding forest use strategies and dependency on production forests, the selectively logged production forests (RFs) in Myanmar were largely depended for income generation by households living both outside and inside the RFs, even though most households knew about the prohibited matter by the forest law. The inside-households (encroachers) were more dependent on the forest for cash income than the outside-households. The main forest use activity of the encroachers was charcoal production while bamboo cutting was the main activity of the outside-households. After the logging ban, the households living adjacent the RFs had reduced forest cash income and total cash income while their non-forest cash income did not change. Farmland size, duration of residency and accessibility to forest were significant factor influencing forest cash income dependency consistently over time. Worse accessibility to the RFs under the logging ban caused lower dependency on the RFs for income generation. Substantial number of households are still depending on the RFs for income generation through charcoal making and bamboo cutting.

Concerning stand structure in illegally logged stand in production forests, illegal logging following legal logging resulted in a substantial reduction in tree stocks, though high frequency of legal logging did not necessarily show a heavily degraded condition in selectively logged production forests. Illegal logging continued for 7 years following repeated legal logging under the short rotation in the production forests of Myanmar. Repeated illegal logging was a major contributor to decreasing the total basal area of plots. Accordingly, bamboo stocks were larger in stands with a lower density of trees (DBH > 10 cm), and in turn, tree regeneration (DBH < 10 cm) was lower in stands with more bamboo stocks. As a conclusion, reduced tree density due to repeated legal and illegal logging indirectly caused less tree regeneration through increasing bamboo stocks.

To improve the management of production forests, implementing community forestry practices should promote effectively to reduce illegal dependence on selectively logged production forests. Moreover, supporting the right to extract NTFPs, such as bamboo, for commercial purposes from nearby production forests might be an incentive for the socio-economic development of forest-dependent rural people and the restoration of widespread degraded production forests in Myanmar. Income generation opportunities should be created by rural development projects. Extension activities are also required to increase the effectiveness of new policy such as the logging ban, and to have local people's active participation in restoration of degraded production forests in Myanmar.

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