Evaluating logging impacts and moving behavior of Asian elephants (Elephas maximus) under Myanmar Selection System

シー, チュー, ミン

出版情報：Kyushu University, 2022, 博士（農学）, 課程博士

Evaluating logging impacts and moving behavior of Asian elephants (*Elephas maximus*) under Myanmar Selection System

SIE THU MINN

2022

Evaluating logging impacts and moving behavior of Asian elephants (*Elephas maximus*) under Myanmar Selection System

A dissertation submitted to the Graduate School of Bioresources and Bioenvironmental Sciences, Kyushu University, Japan, in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Ph.D.)

By

Sie Thu Minn

Table of Content

List of Tables

List of Figures

Acknowledgement

First of all, I would like to express my gratitude to the MEXT (Monbukagakusho) Scholarship program for providing my scholarship, and Extraction Department, Myanma Timber Enterprise (MTE) for granting me permission to study in Japan.

The first person I would like to express my deep thank is Dr. Nobuya Mizoue for his scientific guidance, continuous encouragement, supports and advices through the study in Japan as well as field guidance and supervision even in deep forest of Myanmar.

Dr. Tetsuji Ota who is another person I would like to convey my deep thanks for his supports, advices and also for participating field trips in Myanmar for field guidance. I also would like to express my sincere appreciation to Dr. Yoshihiro Shuin for his kind advices and comments, as a co-examiner of this thesis. I also would like to extend my gratitude to Dr. Shigejiro Yoshida for his valuable comments, advices in seminars and also for his warmth and sincerity. Moreover, I would like to express my thanks to members of Laboratory of Forest Management for creating such warm and wonderful environment.

I am also very grateful to the General Manager of Extraction Department, MTE and the local staff of extraction department of Bago (South) Extraction Agency, Katha (East) Agency especially who supporting me for frequent and long stayed surveys. Without their assistance, it would be impossible to reach my goal.

The work is finally dedicated to my country, department, family, my wife, my beloved son and daughter, and all of my friends for their persistent supports and endless love during the whole study.

Abbreviations

AAC = Annual Allowable Cut
ASEAN = Association of South East Asia Countries
CON = Conventional Logging
DBH = Diameter at Breast Height
DI = Departmental Instruction of Extraction Department
FAO = Food and Agriculture Organizations of United Nations
FD = Forest Department, Myanmar
GBH = Girth at Breast Height
GPS = Global Positioning System
ha = Hectare
ITTO = International Tropical Timber Organization
LUS = Lesser Used Species
m = Meter
m^2 = Squared Meter
MSS = Myanmar Selection System
MTE = Myanma Timber Enterprise
RF = Reserved Forest
RIL = Reduced-Impact Logging
SFM = Sustainable Forest Management
SOS = Standard Orders for Extraction Staff
FMU = Forest Management Unit at District Level

Summary

Timber production is one of the important ecosystem services from tropical forests and has been practiced commonly by selective logging, and also a source of national income in developing countries. However selective logging has been considered as one of the major proximate causes of deforestation and forest degradation in tropics. Under selective logging, reduced-impact logging (RIL) contrary to conventional logging (CON) has been widely recognized as a system practiced by intensively planned and carefully controlled timber harvesting by trained workers in ways to minimize the deleterious impacts of logging. However, the effectiveness of individual RIL practice often depends on site conditions, and supporting data for each RIL practice remain scarce. In Myanmar, a harvesting practice known as Myanmar Selection System (MSS) has been introduced since 1865.Under that system, the use of Asian elephant (*Elephus maximus*) is a prominent feature among Myanmar logging operations. It is assumed that MSS may be a good practice of RIL since it has a long history with adopting elephant skidding compared to mechanical skidding commonly used in other countries. However, there have been very few studies on impacts of MSS operations in comparison with logging in other tropical countries. This study aimed to evaluate damage caused by current MSS operations to soil and residual trees and to compare with other similar studies. Moreover, there is still few studies on the behavior of skidding elephants managed under semi-captive condition which is different from wild elephants and full-captive zoo elephants. The overall objective of this study is to investigate post-harvest impacts of selective logging in the Myanmar Selection System (MSS) in two approaches based on soil disturbance and residual tree damage, to explore the extent of elephant actions and impacts resulting from skidding operations and to support the information of elephant behavioral activity for the conservation of semi-captive elephant population.

To fulfill, the first main objective, in Chapter II, the impacts by three logging operations namely logging road construction, log landing construction and log skidding were measured in two compartments from each of Bago (5C and 14C) in two successive logging season spanning 2014 to 2016 and Katha (45C and 46C) in the single 2017-2018 logging season. Then, the results were compared with similar logging practices both in conventional logging (CON) and reduced-impact logging (RIL). The ground disturbance in the MSS compartments was, respectively, 2.1% and 0.4% in average for logging roads and log landings; it is not significantly different from that for CON and RIL ($p > 0.05$). In contrast, the disturbed area along elephant skid trails (0.9%) is much lower than that for CON (5.2%)

and RIL (4.7%) ($p < 0.05$). A large difference in the width of skid trails was found between elephant skidding (1.0 m) and machinery (CON: 5.5 m, RIL: 4.6 m) ($p < 0.0001$). I conclude that elephant skidding can largely reduce ground disturbance due to much narrower width of the skid trails as compared with machine skidding, while MSS does not differ from the other countries in ground disturbance at logging roads and log landings.

In Chapter III, the second main objectives also evaluated the impacts of MSS in terms of residual tree damage in the same study area as Chapter II. Field measurements were conducted in the same time as in Chapter II. The study adopted a modeling-based approach for estimating of residual tree damage (severe, slight or no damage) along elephant skid trails, logging roads and log landing under the traditional Myanmar Selection System (MSS), with incorporating the effects of tree size (diameter at breast height: DBH cm) and felling intensity (trees ha^{-1}). The multinomial logistic model showed that severe damage more likely occurred for tree with smaller DBH along logging roads and log landing, whereas almost no severe damage existed along elephant skidding trails. The model prediction showed that residual tree damage rates per ha (% ha^{-1}) increased with increasing felling intensity (*fi*,trees ha^{-1}) along skid trails and log landings, but this was not the case for logging roads. I also found that the residual tree damage (% ha^{-1}) due to elephant skidding was much smaller than damage owing to tree felling consistently over different *fi*. I conclude that skidding using elephants contributes the lowest levels of residual tree damage as a whole with comparison to other countries' cases that used machine for skidding.

The semi-captive elephants play an important role in conservation of Asian Elephants (*Elephas maximus*) and also possess the initials for reducing the logging impacts by MSS. There are more than 3000 Asian Elephants managed under Myanma Timber Enterprise (MTE) and more than 1000 of these elephants are involved in skidding operations. To under the moving behavior of semi-captive elephants during skidding season, we studied the movements of elephants during the skidding season. Three elephants were fitted with handheld global navigation satellite systems to collect data on their movements. The elephants were generally located between 0.534 and 0.875 km from the camp with temporary housing of the elephant handler when not skidding (i.e., free time) and between 1.365 and 1.372 km when skidding (i.e., work time). The hourly moving distance during free time (0.622–0.655 km) and work time (1.522 and 1.629 km) did not differ greatly from the hourly moving distance of wild Asian elephants (0.010–1.500 km). The elephants remained within 0.875 km of the camp temporary housing of the elephant handler, and some variation in movements among individuals was observed during free time. Thus, the conservation of forest in areas near the camp temporary housing is important for the well-being of these elephants.

In conclusion, the elephant skidding produced the lowest impacts compared to two other logging operations under MSS. Moreover, it was found that the use of elephant in skidding produced lower impact than mechanical skidding adapted in other countries, both CON and RIL. The movement of semi-captive elephants used in skidding showed similar movement to wild elephants. The finding that elephants rest during free time in sites near the logging camp suggests that it is important to conserve forest and water resources within the logging compartments for sustainable implementation of Myanmar forestry coexisting with an endangered species, Asian elephants.

CHAPTER I
General Introduction

1.1 Background information

Tropical forests, which represents around 44% of the total globally forested areas are ecologically characterized by high diversity of species, high frequency of pollination, common occurrence of mutualisms, high rate of energy flow and a relatively tight nutrient cycle (Keenan et al., 2015; Montagnini and Jordan, 2005; Wilson, 1993). The functions of tropical forests include production (timber, fiber, fuel wood and non-timber forest product), environmental conservation (climate regulation, carbon sequestration and storage, reserve of biodiversity, and soil and water conservation), social benefits (subsistence for local populations and cultures) and, recently the tropical forests also become important in carbon and climate change mitigation (Ellis et al., 2019; Miller et al., 2011; Montagnini and Jordan, 2005; Runting et al., 2019; Sist et al., 2003). In 2011, ITTO estimated that there had been 403 million hectares of production forests under 761 million hectares of the total natural tropical permanent forest estate (Blaser et al., 2011). As a part of the productive services, wood plays as a useful and versatile material. Compared to most available materials, wood is stronger, more workable and more aesthetically pleasing (Wadsworth, 1997).

Selective logging, in which only large trees of commercial species are selectively harvested, is a key component of production activity in tropical natural forests and approximately constituted to 24% of total of tropical forests (Blaser et al., 2011). Generally, selective logging was a system that does not change the forest structures under optimal conditions but stimulates natural regeneration and growth if well planned (Hartshorn 1989 cited by Webb, 1997). On the other hand, selective logging is associated with impacts to residual stand (Bertault and Sist, 1997; Johns et al., 1996; Pereira Jr. et al., 2002; Pinard and Putz, 1996), soil disturbance (Pinard et al., 2000), and conservation of water (Miller et al., 2011), wildlife (Burivalova et al., 2015) and biodiversity (Edwards et al., 2012; Runting et al., 2019). The selective logging includes five phases or operations, which are constructing road network by bulldozers, clearing for log landings or patches, felling and bucking trees, linking felled logs by choker cables, skidding logs for transportation (Johns et al., 1996). Some of the phases potentially produce destructive impacts on forests and thus, the impacts were evaluated for respective operations, which were in all of the operations (Johns et al., 1996), operations except machine maneuvering (Jackson et al., 2002; Feldpausch et al., 2005), tree felling, road constructing and log skidding (Whitman et al., 1997; Medjibe et al., 2013; Khai et al., 2016), tree felling and log skidding (Bertault and Sist, 1997; Sist et al., 1998; Medjibe et al., 2011; Tavankar et al., 2013;Ruslim et al., 2016), only in tree felling in falling gaps (Chheng et al., 2015) Some studies did not specify which logging phases were evaluated (Sist and Ferreira, 2007; Webb., 1997). Consequently, many studies propose better and sound harvesting practices to minimize the impacts by the operations of conventional logging method (CON) (Asner et al., 2004; Bertault and Sist, 1997; Feldpausch et al., 2005; Pinard and Putz, 1996; Shenkin et al., 2015a; Sist et al., 2003). The better and sound practices are called Reduced impact logging (RIL), which carefully controls implementation of harvesting operations to minimize the impact on forest stand and soil (FAO, 2004). Comparatively, RIL has been shown to have great potential in terms of carbon and biodiversity conservation (Bicknell et al., 2014; Miller et al., 2011). However, there are still impacts even in RIL operated areas (Darrigo et al., 2016; Feldpausch et al., 2005; Medjibe et al., 2011), calling for better interventions in the logging operations. Moreover, studies on the impacts of selective logging whether CON or RIL are mostly conducted in specific countries, such as Brazil, Malaysia and Indonesia, where tropical rainforests are dominant, whereas there have been limited studies for countries where tropical seasonal forests are dominant (Poudyal et al., 2018). Moreover, many studies have focused on impacts only from felling and skidding (Bertault and Sist, 1997; Medjibe et al., 2013; Ruslim et al., 2016; Sist et al., 1998; Tavankar et al., 2013) and have not evaluated separately each of individual components of logging operations (Picard et al., 2012).

In Myanmar, a selective logging system called the Myanmar Selection System (MSS) has been practiced since 1856 (Dah, 2004). Under the MSS, forest degradation was reported as a major problematic issue (Mon et al., 2012; Win et al., 2018b, 2018a) and the disturbance by selective logging was reported higher than other disturbance factors such as illegal logging, plantations, shifting cultivation (Shimizu et al., 2017b, 2017a). However, the most of the studies used only forest cover derived from remote sensing as the indicator of disturbance (Mon et al., 2012, 2010; Shimizu et al., 2017a, 2017b; Win et al., 2012b). Investigating immediate collateral damage (Shenkin et al., 2015b) or direct impacts by selectively logging operations is still important especially in terms of soil and residual stand which can only be measured by ground measurement. The logging operations under the MSS are similar to other countries: tree felling, constructions of logging infrastructures such as logging roads and log landings but different in skidding of logs which is conducted by elephants while machines are used in other countries (Brunner et al., 1988; Dah, 2004). The elephants used in skidding are Asian elephants (*Elephas maximus)* and are managed under semi-captive system. The semi-captive system means the elephants are freely ranging after working. The elephants used in MSS stands in high population as more than 1000 while the total population is more than 3000. Using the elephant in logging operations in such extensive amount is unique in Myanmar (Sessions, 2007). Some studies reported the use of elephant would be a potential to reduce the deleterious impacts of skidding operation (Mon et al., 2012; Win et al., 2012a). Khai et al., (2020) tried to evaluate the impacts of elephant skidding but failed for empirical information because it is difficult to detect the impacts at their measurement time three months after operations.

1.2 Research Objectives

The overall objectives of this study are to evaluate post-harvest impacts of selective logging in the Myanmar Selection System (MSS), to explore the extent of elephant actions and impacts resulting from skidding operations and to support the information of elephant behavioral activity for the conservation of semi-captive elephant population. The specific objectives are

1) to investigate the impacts of selective logging in terms of area disturbed and residual tree damage
2) to evaluate the impacts of three logging operations especially for elephant skidding
3) to compare the impacts of MSS to other similar studies both of RIL and CON
4) to track behavioral movement of semi-captive elephants used in skidding and
5) to provide the information based on the outcomes so as to support sustainable forest management.

1.3 Structure of Dissertation

The dissertation includes five chapters in total as in Figure 1-1.

Chapter I introduces the background of this study on selective logging and the impacts of it, the selective logging practices in Myanmar and the use of elephant in logging.

Chapter II evaluates the impacts of logging in terms of ground disturbance by logging operations and compares the results to other selective loggings.

Chapter III tries to predict residual tree damage by logging operations using modeling-based approach and also compares it to that in other studies.

Chapter IV observes the movement behavior of the semi-captive Asian elephants used in skidding to support the information for the conservation of surrounding areas of the elephants

Chapter V concludes upon the research findings and recommended the possible and effective ways for sustainable tropical forestry.

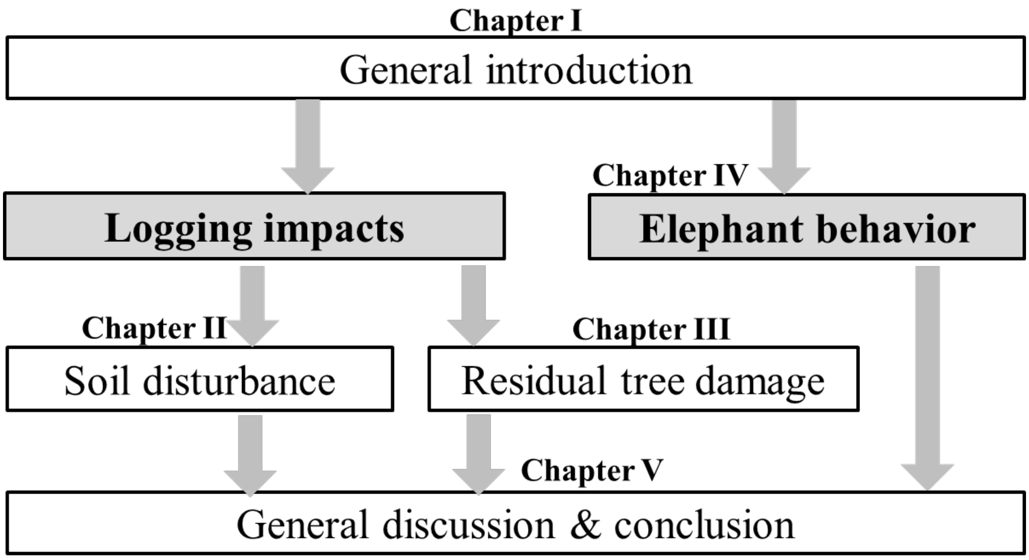

Figure 1-1 Framework of dissertation

CHAPTER II

Evaluating ground disturbance at elephant skid trails, logging roads and log landings under the Myanmar Selection System

2.1 Introduction

Selective logging, where only large trees of commercial species are selected and harvested, is a common practice of timber production in tropical natural forests. Over 20% of the world's tropical forests have been subjected to selective logging (Bicknell et al., 2014). One global concern is that tropical selective logging may result in forest degradation, and reduced-impact logging (RIL) has thus been suggested and practised in many countries (FAO 2004; Poudyal et al., 2018). RIL can be defined as intensively planned and carefully controlled timber harvesting by trained workers, which includes a pre-harvest inventory, marking of trees to be felled, skid trail planning, pre-harvest liana cutting and directional felling (Khai et al., 2016; Sist et al., 2003). In contrast, conventional logging (CON) is conducted by untrained and unsupervised laborers working without the aid of adequate management plans (FAO, 2004). Many studies have evaluated the impacts of CON and RIL in terms of residual tree damage and ground disturbance, and RIL has been shown to have great potential in terms of carbon and biodiversity conservation (Bicknell et al., 2014; Miller et al., 2011). Recent studies on RIL for climate change mitigation have shown that evaluating the performances of individual components of RIL operations, including felling, skidding and construction of log landings and logging roads, is crucial to evaluate the effective adoptions of RIL (Ellis et al., 2019; Goodman et al., 2019; Griscom et al., 2019; Umunay et al., 2019). As pointed in the review by Picard et al. (2012), however, many studies have focused on impacts only from felling and skidding and have not evaluated separately each of individual components of logging operations. In addition, studies on the impacts of selective logging are largely biased toward specific countries, such as Brazil, Malaysia and Indonesia, where tropical rainforests are dominant, whereas there have been limited studies for countries such as Myanmar, Cambodia and Vietnam, where tropical seasonal forests are dominant (Poudyal et al., 2018).

Myanmar has one of the world's longest historical records of practising selective logging, under what is known as the Myanmar Selection System (MSS), beginning in the 19th century (Brunner et al., 1988; Dah, 2004). The major economic species is teak (*Tectona grandis* Linn. f.) while a range of other hardwood species in Myanmar are also harvested and are grouped into five classes based on their economic value (Khai et al., 2016). The felling cycle is 30 years, and the minimum exploitable size depends on the species, with the smallest having a diameter at breast height (DBH) of 58 cm (Khai et al., 2016). The logging phases are classified into (I) tree selection, (II) felling and log bucking, (III) elephant skidding (i.e., gathering logs at log landings using elephants), (IV) constructing log landings and logging roads and (V) transporting logs to depots or sawmills. The state-owned enterprise named Myanmar Timber Enterprise (MTE) is mainly responsible for logging operations (Brunner et al., 1988) while all the stages of tree selection, hammering the official legal stumps and transporting the logs are controlled and checked by the Forest Department as the responsible administrative organization. MSS can be regarded as a form of RIL because the operations are conducted by trained staff and workers, including a pre-harvest inventory, marking of trees to be felled, and directional felling.

Even though the MSS has a long history of practice, recent studies indicated that forests selectively logged under the MSS have degraded widely (Mon et al., 2012; Win et al., 2018b, 2018a). However, it is not well known in Myanmar, as in other countries, which and to what extent logging operations cause forest degradation, relative to other factors such as illegal logging, climate change and forest fire. Thus, evaluating the impact of each logging operation is the first step to discovering the drivers of forest degradation and further improving logging operations. Khai et al. (2020) evaluated felling damage to residual trees and ground disturbance caused by elephant skidding and the construction of roads and log landings within the MSS and concluded that the impacts on residual stands increased with harvesting intensity and were at the lowest level of those reported for other tropical countries. However, their field measurements were limited to one relatively small rectangular plot of 9 ha for each of four compartments where the compartment area ranged from 176 to 740 ha. Such an evaluation only at a small area may overestimate or underestimate the logging impacts at the whole compartment scale, because places, where selective logging operations were conducted, are not necessarily distributed evenly over the whole compartment area. Their comparisons with other countries' data were based on pooled data of three components of ground disturbance (skid trails, logging roads and log landing). No study has investigated the compartment-scale impact of each logging operation in the MSS.

A specific feature of the MSS in Myanmar is that the MSS still uses elephants for skidding, while logging roads and log landings are constructed using machines. Historically, the elephant was largely used in certain Southeast Asian countries, such as Myanmar, India, Laos, Sri Lanka and Thailand (Sessions, 2007), but no county other than Myanmar is currently using elephants for skidding as a part of extensive forestry operations. The number of elephants under MTE's management was reported as 3122 in December 2018. We may hypothesize that ground disturbance due to elephant skidding is less than those due to machine skidding. However, no study has detected and evaluated the effects of elephant skidding immediately after skidding operations. Khai et al., (2016, 2020) tried to evaluate ground disturbances due to elephant skidding but they failed to detect the impacts of elephant skidding because their measurements were made in the dry season (March), 3 months after the felling and skidding operations, and litter falls from deciduous trees during the dry season hindered ones from detecting ground disturbance that had been caused during the operations.

The objective of this chapter is to evaluate ground disturbance caused by logging operations at a compartment scale in Myanmar. In this study, ground disturbance is characterized as the removal of at least the top soil or A0 layer. The specific questions to be addressed are as follows:

(1) Is ground disturbance caused from MSS operations in Myanmar larger or smaller than that from logging in other countries? In particular, is the impact of elephant skidding under the MSS less than that of machine skidding in other countries?

(2) Among three components of the MSS logging operations, namely elephant skidding, the construction of log landings and the construction of logging roads, which causes the most ground disturbance?

It is known that ground disturbance resulting from logging operations often increased with increasing harvesting intensity, and the relationship between ground disturbance and harvesting intensity can be expressed using a linear model (Khai et al., 2016; Khai et al., 2020; Webb., 1997). Thus, we compared not only average (or median) values of ground disturbance but also coefficients of linear models for the relationships between ground disturbance and harvesting intensity. The present study does not intend to encourage other countries to use elephants and other animals for skidding as in the past. Rather, this study searches for a way to further improve logging operations in Myanmar and even other countries where elephants will not be used for skidding.

2.2 Methods

2.2.1 Study sites

I conducted surveys at two sites; a site in Bago, which is the legendary birthplace of the Myanmar Selection System (MSS), and a site in Katha, a famous northern logging concession region (Figure 2-1). The Bago and Katha sites are respectively located at 17° 40' N, 96° 0' E and 23° 53' N, 95° 58' E. The mean annual rainfalls and temperatures are respectively 3089 and 1532 mm and 26.7 and 25.1 °C. The soil types fluvisols and lithosols and elevation ranges of 70 to 153 m and 203 to 345 m above sea level were recorded along the logging roads. At each site, I surveyed two compartments (namely 5C and 14C in Bago and 45C and 46C in Katha). The topography of all the compartments is generally mountainous with steep slopes. General information is provided for each compartment in Table 2-1. The latest logging operations were conducted in two successive logging seasons spanning 2014 to 2016 in 5C and 14C in Bago and in the single 2017–2018 logging season in 45C and 46C in Katha. The recorded history of official logging in the last 10 years was not available for any compartment before the latest logging. Two governmental extraction agencies, namely the Bogo (South) and Katha (East) agencies, conducted logging operations in each area.

Trees to be felled were selected by skilled and experienced Forest Department officials. The minimum DBH of trees was determined as 58.2 cm (a local limit of 6 ft. in girth). Some trees, such as would-be seed trees, trees with defects and non-profitable trees over the DBH limits were not selected or felled. Meanwhile, some trees, such as half-dead trees, badly burnt trees and ones with partial defects but still possessing some economic values were considered for felling. Trees were felled and cut into logs by trained operators using chainsaws. Average size (± standard deviation) of logs in our study sites was 6.4 ± 1.1 m in length and 57.3 ± 13.2 cm in diameter at the middle of the logs. Logs were then collected and dragged to pre-determined log landings by trained staff using elephants. The chains were attached to the saddle of the elephant, and the other end of the chains was tied directly to the log without using a skidding cone (Figure S 1-1). The logs were normally hauled completely on the ground. During the working season from June to February, one elephant drags about 270 m^3. The log landings and logging roads were constructed using D65 bulldozers. Trucks transported the logs to sawmills or more accessible depots. After the completion of the harvesting process, the compartment was inspected again by the Forest Department.

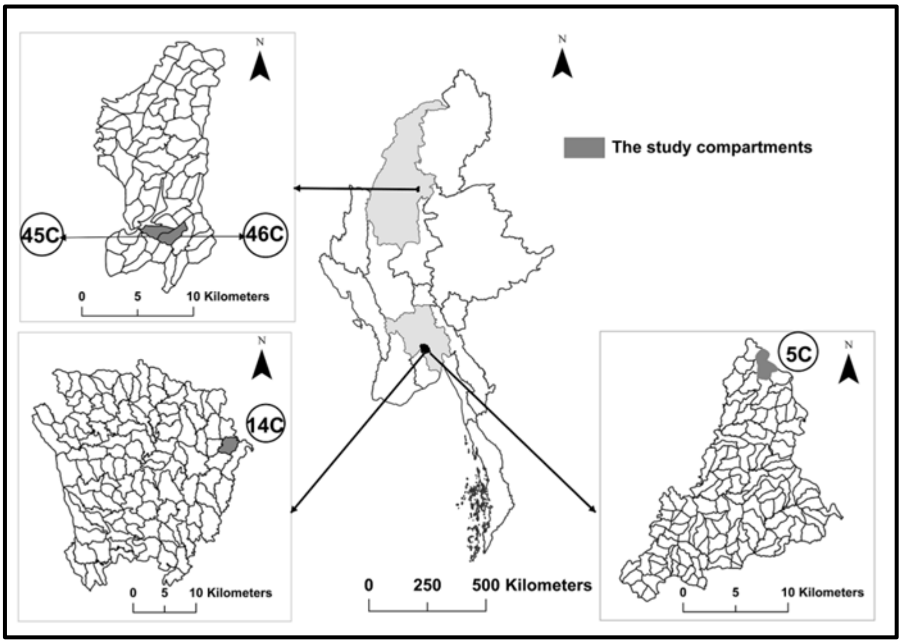

Figure 2-1 Locations of surveyed compartments; 5C and 14C in two reserved forests of the southern region of Bago and 45C and 46C in one reserved forest of the northern region of Katha in Myanmar

Table 2-1 General information of the study sites

Region	Bago area		Katha area	
Reserved Forest	Shwelaung Kodukwe	(1) South Zama ye	Pyinde	Pyinde
Compartment	5C	14C	45C	46C
Whole area (ha)	280	622	176	213
Operational area (ha)	280	207	136	213
Soil types	Fluvisols	Fluvisols	Lithosols	Lithosols
Logging intensity				
Tree number (trees ha^{-1})	1.6	2.1	1.1	1.5
Log volume (m^3 ha^{-1})	5.4	4.3	4.9	5.0

2.2.2 Field measurements and data analysis

I measured the area of ground disturbance along elephant skid trails, along logging roads and at log landings. A skid trail can be easily distinguished from a logging road in terms of the size and location. The former is much narrower and arose by an elephant that drags the logs from the place where a tree is felled down to the log landing while the latter is wider and constructed with a bulldozer for the use of the truck to transport the logs from the log landing to the sawmill. As in other studies, we defined ground disturbance as the removal of at least the top soil or A0 layer during operations along skid trails, along logging roads and at log landings. We calculated the ground disturbance percentages (%) of each operation against the operational areas of the compartments shown in Table 2-1.

Field measurements were made during the logging seasons of 2014–2016 in Bago and 2017–2018 in Katha. The logging season starts from May or June with the selection of trees to be felled and felling. Then, the skidding operation is conducted after the felling operation and continues till the middle of February. The log landings and logging roads are constructed when the rainy season ends in late September or early October. The logging operations usually end in April with transporting the logs to sawmills using trucks. In this study, the measurements of skid trails were conducted from September to December within one week after the elephant skidding operations because it is difficult to clearly trace and measure skid trails some weeks after the operations (Khai et al., 2016; Khai et al., 2020). The measurements of logging roads and log landings were conducted in January or March.

2.2.2.1 Skid trails

In the study sites, a skid trail has a branching network that is connected to one log landing, like a river connecting a lake. A first-order segment of a skid trail network begins with the point of tree felling, and when the two first-order segments combine they forms a second-order segment, and so forth. The last-order segment is connected to one log landing. Usually, one log landing is linked to some skid trail networks.

Owing to time constraints, I did not measure all skid trail networks for 4 compartments. but rather we measured only samples of skid trail networks. Then, using the measured sample data, we developed a generalized linear model (GLM) to predict ground disturbance (%) at the compartment scale, based on the findings that ground disturbance is closely related with harvesting intensity (Webb1997, Khai et al., 2020). In this study, I used the software R (R Core Team, 2021) for GLM analysis and statistical tests.

During the field works, we randomly selected 11 and 7 log landings among a total of 21 and 22 that existed in 45C and 46C, respectively. Then, I measured all the skid trail networks that were connected to the selected log landings. As a result, we measured 31 and

14 skid trail networks among a total of 53 and 75 that existed in 45C and 46C, respectively. We did not measure any networks in 5C and 14C.

For each of a total of 353 segments in 45 skid trail networks, I measured the length (a total of 7493 m), longitudinal slope angle and azimuth from the starting to ending points using a laser instrument (TruPulse 360R™). I also measured the debris width (Figure 2-2) of the disturbed area at starting, middle and ending points of each segment using a fiberglass tape. For the area calculation of each segment, I used the average width at the three points multiplied by the length of each segment.

For each segment, I recorded which and how many trees/logs were skidded using elephants by checking the serial number of each stump and the spatial location of stumps within a skid trail network. Each stump was marked by the tree number and log number. As an example, 100/3 was marked on the stump of tree number 100 to show that three logs were produced from the tree with serial number 100. We also rechecked the number of logs actually produced from the tree with hummer marks on the logs, which were piled up in the log landing. The identification was conducted with the help of the timber ranger who was in-charge of the compartment and the elephant staff who performed the skidding of the logs.

The total disturbed area for each skid trail network with a branching pattern was calculated as a total area for the segments constituting each network. I summarized data on the relationship between the harvesting intensity (*HI*) and ground disturbance area (*GDA*, m^2) for each skid trail network (n = 45). As *HI*, we calculated the number of trees (*TN*, trees) or stem volume (*SV*, m^3) of skidded trees for each skid trail network, because these variables are commonly used in other studies. Based on the preliminary analysis of our data, I assumed that the relationship between *HI* and ground disturbance can be expressed as a power law:

$$GDA\ (m^2) = \alpha \times HI^{\beta}\ (\text{trees or } m^3) \quad (1)$$

where *HI* is either *TN* (trees) or *SV* (m^3), and α and β are coefficients of the equation.

I also assumed that this relationship for each skid trail network can be expressed on a per unit area (1 ha) basis;

$$GDA\ (m^2\ ha^{-1}) = \alpha \times HI^{\beta}\ (\text{trees } ha^{-1} \text{ or } m^3\ ha^{-1}) \quad (2)$$

The percentage of the disturbed area on a per unit area basis (GDP, %) is then expressed by dividing by 10^4 to convert to the m^2 unit and multiplying by 10^2 to convert to the % unit as

$$GDP\ (\%) = GDA \times 10^{-4} \times 10^{2} = 10^{-2} \times \alpha \times HI^{\beta} = \alpha' \times HI^{\beta} \quad (3)$$

where α’ is 10^{-2}×α. I used Equation (3) to estimate the disturbed area (%) for each compartment by inputting the harvesting intensity *HI* (*TN* trees ha^{-1} or *SV* m^3 ha^{-1}) at the compartment scale, as shown in Table 2-1. In estimating the parameters of Equation (3), I used GLM with a Gamma distribution and log-link function for the response variable *GDP* and explanatory variable log (*HI*). I also estimated the length density (m ha^{-1}) of skid trails for each compartment, which is skid trail length on a per unit area basis, and calculated it as *GDA* on a per unit area basis (m^2 ha^{-1}) divided by the average width (=1.0 m) of skid trails.

2.2.2.2 Logging road

I measured all the logging roads constructed in all four compartments, from the starting point where a road approached a compartment to the end point of the road network. I divided all roads into straight line segments connecting two points that were located at the middle of the road width. In each segment, I measured the length, slope angle and azimuth using a laser instrument (TruPulse 360R™). I measured the width of logging roads every 10 m along eight randomly selected 100-m-long sections in each compartment except 46C, where measurements were made in 12 sections. As a result, the total number of measurement points was 360. Following the definition made by Johns et al. (1996), I measured three different widths (i.e., the road width, berm width and debris width) at each measurement point using a fiberglass tape (Figure 2-2). Areas resulting from dead ends and operator faults were also considered as part of the logging road and measured. Some mechanical movement by the bulldozers around log landings was also measured as the logging road. The area of the ground disturbance in each compartment was calculated as the total length of logging roads (calculated by totalling the length all line segments) multiplied by the mean road width (calculated as the mean of all debris width measurements as shown in Figure 2-2). The geographical positions of the logging roads were recorded using a Global Positioning System device (Garmin 60CSx®).

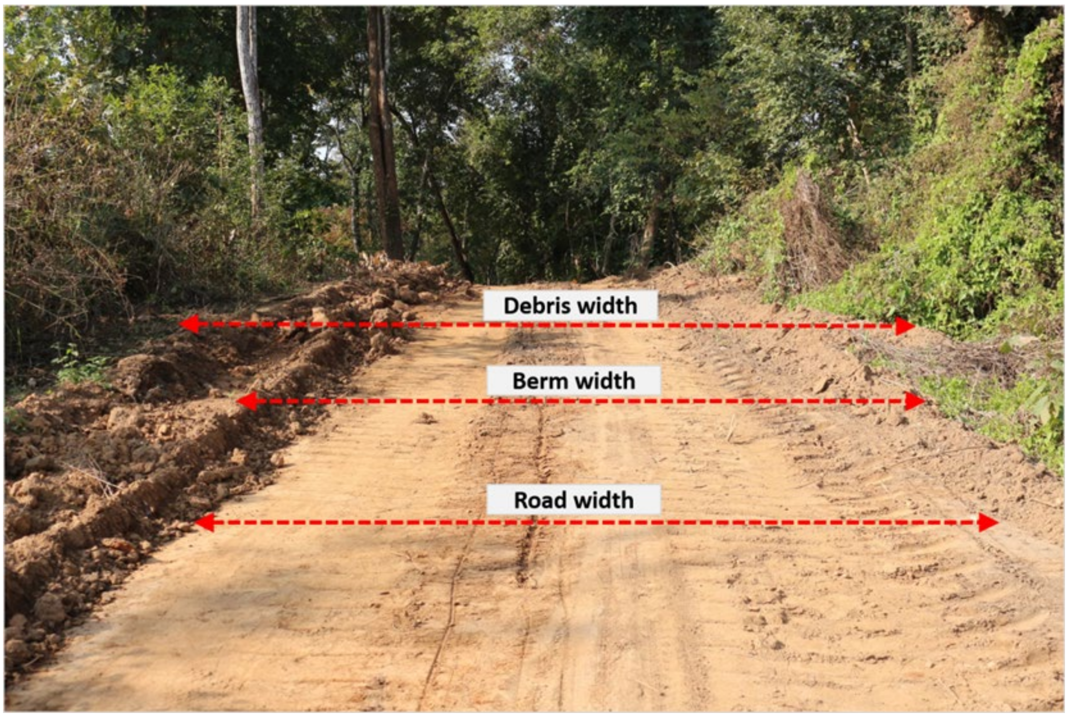

Figure 2-2 Measurements of the road width, berm width and debris width

2.2.2.3 Log landings

I recorded the geographical position near the center of all the log landings in all four compartments using a Global Positioning System device (Garmin 60CSx®). In compartments 14C, 45C and 46C, we measured the area of ground disturbance at 22, 21, and 23 log landings respectively using a laser instrument (TruPulse 360R™) by applying the center-point system (Runkle, 1992), a system of summing the area of six triangles based on the distance from the center to the edge of the log landing. In 5C, I measured only the position and did not measure the area owing to time constraints.

2.2.2.4 Comparisons with other studies

I compared and tested our data on the ground disturbance (%) along logging roads, at log landings and along skid trails with recorded values in published studies on RIL and CON in other countries, where only machines such as bulldozers or tractors were used. Some studies classified operations into certified and non-certified operations (and not into CON and RIL operations), and our study regarded these certified and non-certified operations as RIL and CON, respectively, for the ease of comparing data. Among a number of studies focusing on ground disturbance by tropical selective logging, I selected studies that had the same variables as our study: i.e., harvesting intensity in terms of the tree number (trees ha^{-1}) and/or stem volume (m^3 ha^{-1}) and percentage area disturbed by logging roads, log landings, and skid trails. I compared and tested our data of ground disturbance with those of 17 published studies including 32 sample blocks (Table S 2-1) and those of data from 61 sample blocks compiled by Ellis et al., (2019) (Table S 2-2). Data compiled by Ellis et al., (2019) did not explicitly showed ground disturbance areas. Thus, we estimated disturbed areas of logging roads and skid trails through multiplying the length density (m ha^{-1}) by the average width (m). The compiled data did not include skid trail widths in some sample blocks, and in these cases, we obtained the width data from the original articles (Goodman et al., 2019; Griscom et al., 2014; Zalman et al., 2019). For log landing, their data showed carbon emissions arising from construction of log landing per ha (Mg C ha^{-1}) and average carbon density of adjacent unlogged forest block per ha (Mg C ha^{-1}). Assuming that log landing is constructed by clear cutting the unlogged forest, we estimated disturbed areas of log landings through using the values of carbon emissions from construction of log landing (Mg C ha^{-1}) dividing by the carbon density of adjacent unlogged forest (Mg C ha^{-1}), as in Khai et al., (2020).

For multiple comparisons in ground disturbance (%) among logging methods (CON, RIL and the MSS), first, I performed the Kruskal-Wallis test followed by the post-hoc Steel-Dwass test using the NSM3 package of the software R. It is known that ground disturbance (%) depends on the harvesting intensity. Second, we thus used a GLM with a Gamma distribution and log-link function to relate ground disturbance (*GD*, the response variable) with harvesting intensity (*HI*, explanatory variable) and to compare this relation among logging methods (CON, RIL and the MSS) as dummy variables;

$$\text{Log}\ GD = \beta_0 + \beta_1 \log HI + \beta_2 D_{MSS} + \beta_3 D_{RIL} \quad (4)$$

where D_{MSS} and D_{RIL} are dummy variables; (D_{MSS}, D_{RIL}) is (0, 0), (1, 0) and (0,1) when the logging method is CON, MSS, RIL, respectively, and CON is treated as the reference level. Then, we evaluated differences in ground disturbance changing with harvesting intensity among CON, MSS, RIL based on significant levels of the dummy variables' coefficients (β_2 and β_3).

I also applied the Kruskal-Wallis test followed by the post-hoc Steel-Dwass test to compare widths (m) and density (m ha^{-1}) of skid trails and logging loads with data from 16 references listed in Table S3 and from 61 sample blocks compiled by (Ellis et al., 2019) (Table S 2-2).

2.3 Results

2.3.1 Skid trails

In order to estimate ground disturbance (%) along elephant skid trails at the compartment scale, we developed GLMs using harvesting intensity in terms of the stem volume (*SV*, m^3 ha^{-1}) and number of harvested trees (*TN*, trees ha^{-1}) (Equation 3, $p < 0.0001$, AIC = 94.7 for *SV* and 72.8 for *TN*, Figure 2-3, Table S 2-4). As a result, a ground disturbance was 0.9 % or 0.7% on average under a harvesting intensity of *SV* or *TN* respectively ranging from 4.3 to 5.4 m^3 ha^{-1} or from 1.1 to 2.1 trees ha^{-1}, for the four compartments, as shown in Figure 2-4 and Table 2-2.

The ground disturbance for the MSS (mean ± standard deviation = 0.9 ± 0.08 %, $n = 4$, Figure 2-5) was significantly smaller than that for CON (5.2 ± 4.3 %, $n = 55$, $p = 0.008$) and RIL (4.7 ± 3.9 %, $n = 31$, $p = 0.012$), while no significant difference existed between CON and RIL ($p = 0.923$). The GLM results (Table S 2-5, Figure 2-4) indicated that ground disturbance (%) increased with harvesting intensity in terms of the stem volume and number of harvested trees ($p < 0.0001$). The ground disturbance for the MSS was lower than that for CON consistently for both the stem volume and number of harvested trees as the harvesting intensity ($p < 0.0001$), while RIL was different from CON for the number of harvested trees ($p = 0.015$) but not for the stem volume ($p = 0.152$).

The width of skid trails for the MSS (1.0 ± 0.4 m, $n = 339$, Figure S 2-1, Table 2-2) was significantly narrower than that for CON (5.5 ± 2.7 m, $n = 51$, $p < 0.0001$) and RIL (4.6 ± 1.7 m, $n = 27$, $p < 0.0001$), while no significant difference existed between CON and RIL ($p = 0.50$). The length density of skid trails was not significantly different among CON (84.9 ± 48.6 m ha^{-1}, $n = 52$), RIL (73.7 ± 39.4 m ha^{-1}, n = 24) and the MSS (85.5 ± 7.9 m ha^{-1}, $n = 4$) ($p = 0.4844$, Figure S 2-2).

Table 2-2 Size and ground disturbance of skid trails, logging roads and log landings

Compartment	5C	14C	45C	46C	Average
Skid trails					
Area of ground disturbance (%)*					
estimated from stem volume (*SV*)	0.9	0.8	0.9	0.9	0.9
estimated from tree number (*TN*)	0.7	1.0	0.5	0.7	0.7
Average width (m)	n.a.	n.a.	1.0	1.0	1.0
Density (m ha^{-1})**	94.0	75.0	85.6	87.3	85.5
Logging roads					
Area of ground disturbance (%)	2.0	1.6	1.8	2.9	2.1
Average width (m)	8.6	6.0	6.4	6.6	6.4
Density (m ha^{-1})	24.0	26.9	27.7	43.5	30.5
Log landings					
Number in the compartment	24	26	21	32	25.8
Area of ground disturbance (%)	n.a.	0.4	0.5	0.4	0.4

*The ground disturbance area (%) was estimated based on Equation (3) for the relationship between ground disturbance (*GDP*, %) and harvesting intensity in stem volume (*SV*, m^3 ha^{-1}) or tree number (trees ha^{-1}) for skid trail networks ($GDP=0.181101SV^{0.9777}$ *or* $GDP=0.419664TN^{1.1470}$) as in Figures 2-3 and 2-4.

**The density (m ha^{-1}) was calculated by dividing the ground disturbance area (m^2) estimated for each compartment by the average width of skid trails (1.0 m).

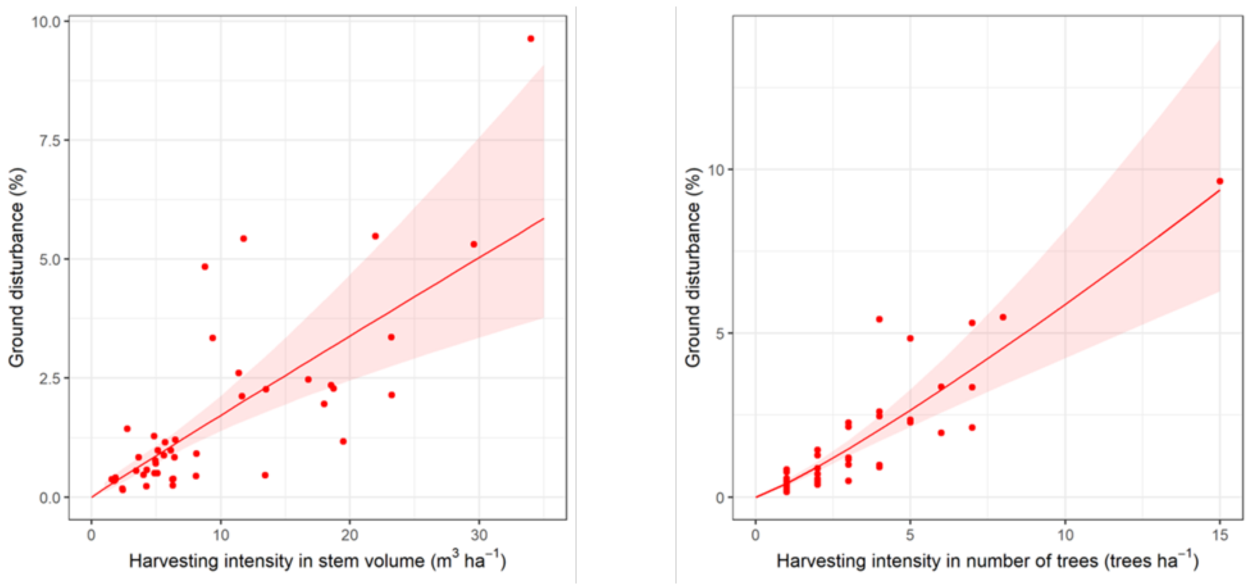

Figure 2-3 Relations between ground disturbance (*GDP* %) and harvesting intensity in terms of the stem volume (left; *SV* m3 ha−1) and number of trees (right; *TN* trees ha−1) for each of 45 elephant skid trail networks, where Equation (3) is *GDP* = 0.181101*SV*0.9777 (Nagelkerke's pseudo *R2* = 0.729) and *GDP* = 0.419664*TN*1.1470 (Nagelkerke's pseudo *R2* = 0.842) (Table S 2-4). The filled light red indicates the range of its 95% confidence intervals of the model prediction.

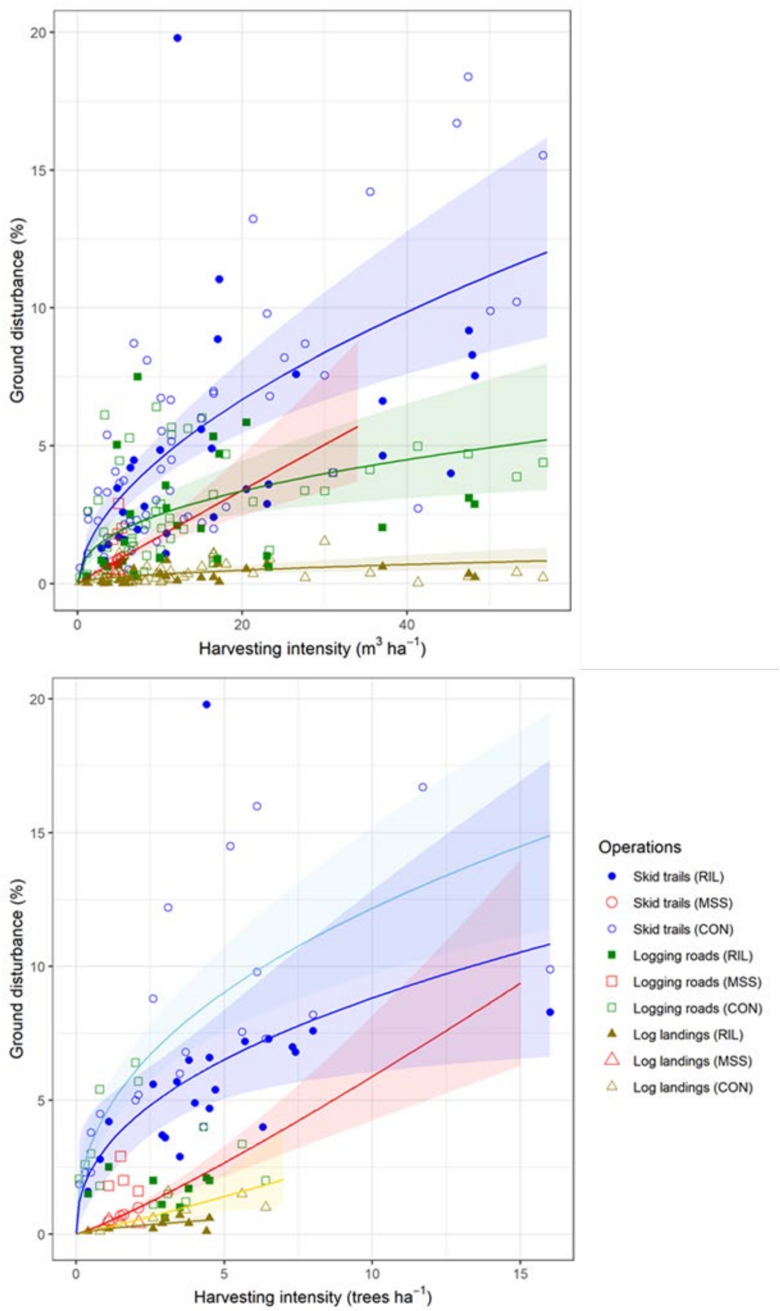

Figure 2-4 Ground disturbance (%) along skid trails for CON (n = 55), RIL (n = 31) and the MSS (n = 4). The boxplots indicate the minimum, first quartile, median (bold line), third quartile (Q3), maximum and outliers (open circles). The different alphabets (a and b) in the graph area between two pairs among CON, RIL and the MSS indicate that there is significantly different ($p < 0.05$) based on the post-hoc Steel-Dwass test, while the same indicates no significant difference.

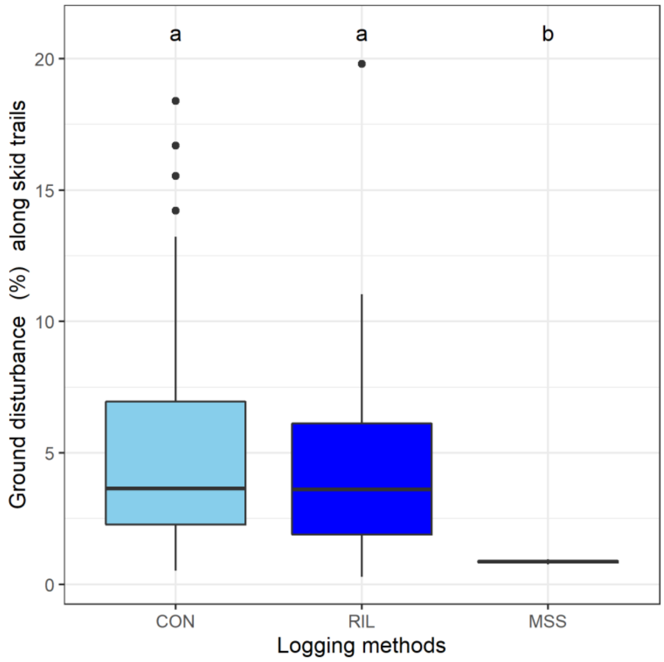

Figure 2-5 Ground disturbance (%) along skid trails for CON (*n* = 55), RIL (*n* = 31) and the MSS (n = 4). The boxplots indicate the minimum, first quartile, median (bold line), third quartile (Q3), maximum and outliers (open circles). The different alphabets (a and b) in the graph area between two pairs among CON, RIL and the MSS indicate that there is significantly different ($p < 0.05$) based on the post-hoc Steel-Dwass test, while the same indicates no significant difference

2.3.2 Logging roads

The ground disturbance along logging roads under the MSS was 2.1% on average and similar (ranging from 1.6% and 2.9%) among the four compartments (Table 2-2). The value is not significantly different among CON (2.6 ± 1.9 %, *n* = 50), RIL (2.4 ± 2.0 %, *n* = 25) and the MSS (2.1 ± 0.57 %, *n* = 4) ($p = 0.8504$, Figure 2-6). The GLM results (Table S 2-5, Figure 2-4) indicate that ground disturbance (%) increased with harvesting intensity in terms of the stem volume ($p < 0.0001$) and CON did not significantly differ from RIL ($p = 0.574$) and the MSS ($p = 0.811$). Meanwhile, the ground disturbance did not depend on the number of harvested trees ($p = 0.981$).

The width of logging roads for the MSS (6.9 ± 2.03 m, *n* = 360, Figure S 2-2, Table S 2-4) was significantly narrower than that for CON (21.8 ± 12.2 m, *n* = 50, $p < 0.0001$) and RIL (20.8 ± 11.4 m, *n* = 25, $p < 0.0001$) , while no significant difference existed between CON and RIL ($p = 0.897$). The length density of logging roads was not significantly different among CON (13.9 ± 10.8 m ha^{-1}, *n* = 10), RIL (15.8 ± 6.2 m ha^{-1}, *n* = 7) and the MSS (30.5 ± 8.8 m ha^{-1}, *n* = 4) ($p = 0.062$, Figure S 2-4).

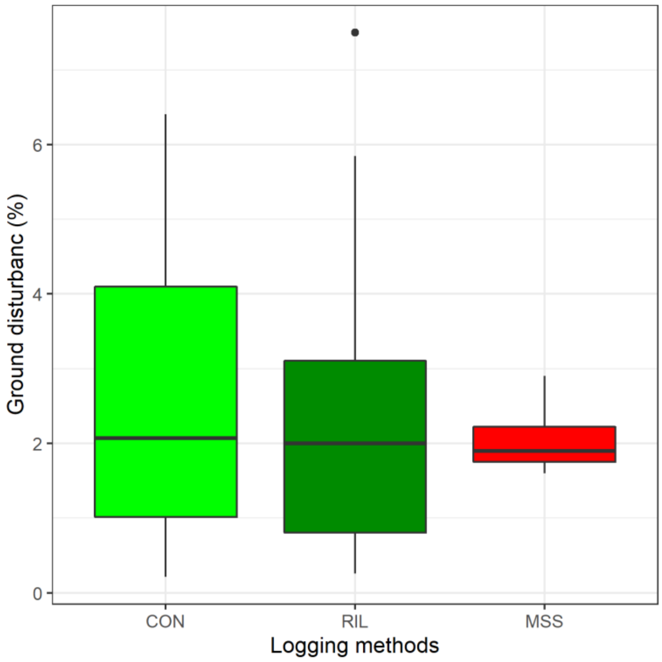

Figure 2-6 Ground disturbance (%) along logging roads for CON (*n* = 50), RIL (*n* = 25) and the MSS (n = 4)

2.3.3 Log landings

The ground disturbance at log landings of the MSS was 0.4% on average, ranging from 0.4% to 0.5% among the three compartments (Table 2-4). The value did not differ among CON (0.3 ± 0.3 %, $n = 46$), RIL (0.3 ± 0.3 %, $n = 26$) and the MSS (0.4 ± 0.058 %, $n = 3$) ($p = 0.5407$, Figure 2-7). The GLM results (Table S 2-5, Figure 2-4) indicate that ground disturbance (%) increased with harvesting intensity ($p < 0.0001$), and the results for CON did not significantly differ from those for RIL ($p = 0.393$) and the MSS ($p = 0.256$) with a change in harvesting intensity in terms of the stem volume. In terms of using the number of harvested trees as the harvesting intensity, results for CON did not differ from those for the MSS ($p = 0.685$) but were lower than those for RIL ($p = 0.043$).

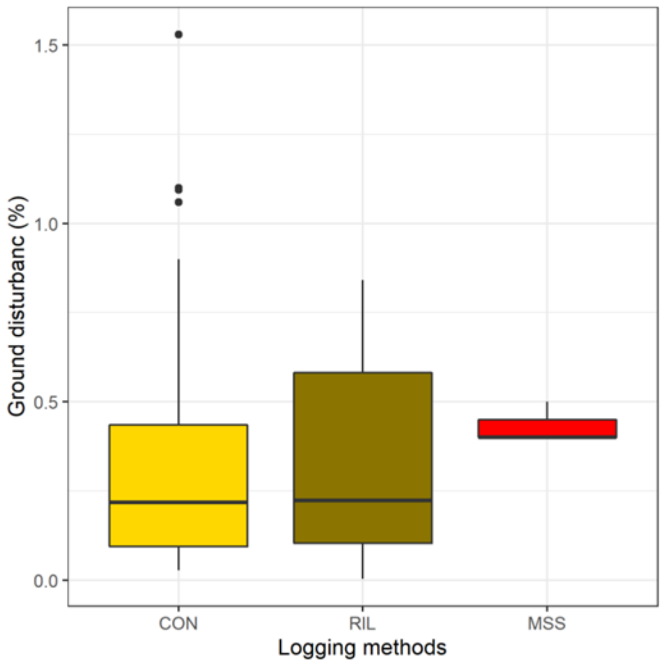

Figure 2-7 Ground disturbance (%) at log landings for CON (*n* = 46), RIL (*n* = 26) and the MSS (*n* = 3)

2.4 Discussion

The present study investigated how impacts from MSS operations using elephants for skidding are different from those of machine-only-based operations. Our results show large differences in ground disturbance between MSS skidding operations and other skidding operations while the results for logging roads and log landings do not differ or only slightly differ between the MSS and other systems (Figure 2-4).

It is known that in tropical forestry operations there is much more ground disturbance along skid trails than along logging roads and at log landings. Skid trails were the largest contributor to the overall ground disturbance in the range of 3.0%–12%, whereas log landings and logging roads were small components of the ground damage, usually accounting for less than 1% and 2% of the ground damage respectively (Asner et al., 2004, Feldpausch et al., 2005). This may be because the same logging roads or log landings are likely used to operate much more logs within the compartment while the same skid trails are used to drag only a few logs, and thus more skid trails are needed. In contrast, our results for Myanmar show that ground disturbance associated with elephant skid trails (0.9 ± 0.08 %) was much smaller than that associated with logging roads under the MSS (2.1 ± 0.57 %) and was lower than disturbances reported in other studies (Figure 2-4, Figure 2-5). One reason for such low-level disturbance from elephant skidding is that the skid trails are much narrower for elephant skidding (1.0 ± 0.4 m) than for machine skidding (5.5 ± 2.7 m for CON, 4.6 ± 1.7 m for RIL) (Figures S 2-1), while the length density of elephant skid trails (85.5 ± 7.9 m) is not different from that of machine skid trails (84.9 ± 48.6 m for CON, 73.7 ± 39.4 m for RIL) (Figure S 2-2). Bulldozers or wheeled skidders (at least 3.0 m in width) that are usually used for skidding easily disturb soils with at least 3.0-4.0 m machine widths during skidding (Johns et al., 1996). Meanwhile, we observed in our field survey that soil disturbance due to elephant footprints was almost negligible, and disturbed areas during elephant skidding arose not from the elephant movement itself but from the logs that were dragged by the elephants. Therefore, widths of elephant skid trails are affected mainly by the size of logs, which are mostly less than 100 cm in diameter. We also found that the logging roads were appreciably narrower for the MSS (6.9 ± 2.0 m) than for the other countries (21.8 ± 12.2 m for CON, 20.8 ± 11.4 m for RIL), even though the MSS also used a bulldozer as in the other countries. This difference in the road widths may be due to most logging road construction involving much wider corridors than just the road track itself for traffic safety reasons and to let the sun dry the road surface after rain (Kleinschroth et al., 2016), while such road construction is not common for the MSS, which is adopted mostly in mountainous regions. Although the types of the trucking vehicle are not provided in many studies, the resulting width may be different owing to the types of truck used in transporting logs. Another reason may be the road type because most of the roads constructed in the compartments are only seasonal or temporary roads for use in the dry season.

Increasing attention has been paid to RIL, which has the potential to enhance various ecosystem services, such as the conservation of biodiversity (Runting et al., 2019), carbon (Sist et al., 2003) and water (Miller et al., 2011), in selectively logged tropical forests. It is thus important to quantify the effectiveness of each RIL operation. Our study indicated that effectiveness in terms of reducing ground disturbance did not differ among CON, RIL and the MSS for logging roads and log landings (Figures 2-6 and 2-7). For skid trails, the lowest level of ground disturbance was confirmed for MSS (Figures 2-4 and 2-5), and RIL had a level lower than CON when taking into account the dependency of the harvesting intensity in terms of the number of harvested trees although the difference between RIL and CON did not differ with a change in the harvesting intensity in terms of the stem volume (Figure 2-4). This finding is in alignment with those of Pinard et al., (2000) and Asner et al., (2004a) who found that ground disturbance from skid trails in CON was significantly higher than RIL, but they could not find a significant difference in the road area between CON and RIL. Further, according to their report, using a ca. 100 m winch cable instead of using bulldozer blades can be the main reason for declining the ground disturbance on skid trails in RIL, compared to CON (Griscom et al., 2014). When the skidder stops while logs are dragged by winching a long cable, the situation of ground disturbance may be somewhat similar to that during elephant skidding; ground disturbance arises only from logs that are being dragged and not from movements of the skidder machines or elephants. The results of our study encourage the use of a longer line winch when machine skidding in other countries so as to minimize the movement of the machines and thus further reduce the ground disturbance. Meanwhile, we also should consider that damage to residual trees (not to the ground) may increase when using a longer cable, but we can improve winching using a snatch block for changing the pulling direction to prevent residual tree damage (Picchio et al., 2012).

It is also known that ground disturbance tends to increase with increasing harvesting intensity (Khai et al., 2016; Pereira Jr. et al., 2002). However, the cited studies did not distinguish components of ground disturbance, such as skid trails, logging roads and log landings. Our study showed that there was a dependency of ground disturbance on harvesting intensity in terms of the stem volume (m^3 ha^{-1}) for all the components of skid trails, logging roads and log landings, although a dependency on the number of harvested trees was not found for logging roads (trees ha^{-1}) (Figure 2-4). Gullison and Hardner (1993) presented simulation results where the ground disturbance (%) was constant with increasing harvesting intensity for logging roads but increased with increasing harvesting intensity for skid trails. These results demonstrate that the harvesting intensity should be considered when evaluating the ground disturbance, at least along skid trails. My results in Figure 2-4 confirm that ground disturbance along skid trails is lowest for the MSS, at least under a lower harvesting intensity of less than about 20 m^3 ha^{-1} or less than about 7 trees ha^{-1}, followed by RIL and CON. The increase in ground disturbance with harvesting intensity was curvilinear with convex form for RIL and CON whereas an almost linear relation was found for the MSS (Figures 2.3 and 2.4). Such curvilinearity was also found in the overall ground disturbance (skid trails + logging roads and log landings) (Khai et al., 2016), likely because the same skid trails or logging roads may be used for more harvested trees when the harvesting intensity increases. The reason for the linearity in the case of the MSS skid trail is not clear, but the relatively low stand density in mixed deciduous forests in Myanmar (188 ± 60 trees ha^{-1} for a DBH exceeding 10 cm, mean ± standard deviation of eight 1-ha plots in pre-harvest stands; Khai et al., 2020) may make it more difficult to use the same skid trails efficiently. The ground disturbance along skid trails may be also affected by various site conditions, such as the microtopography, terrain slope and soil types (Putz et al., 2008). Further research under different site conditions is thus needed to generalize the estimation of ground disturbance along elephant skid trails.

2.5 Conclusion

My study evaluated ground disturbance under the operation of traditional tropical forestry in Myanmar, the so-called MSS, using elephants for skidding as compared with machine-only-based operations conducted in other countries. The following conclusions are drawn from the results of the study.

(1) In comparison with cases in other countries, the ground disturbance of the MSS is lower along skid trails but not different along logging roads and at log landings.

(2) In logging operations of the MSS, ground disturbance is greatest along logging roads (1.9%), followed by elephant skid trails (0.9%) and then log landings (0.4%).

The lowest level of disturbance along elephant skid trails resulted from widths (median of 0.9 m) being much narrower than those of machine skidding (median of 4.3 m). Such narrow disturbance arises from the logs that are dragged by elephants, whereas elephant movement itself does not cause ground disturbance distinctly. My results encourage the use of long winch cables in machine skidding to minimize the movement of machines and thus reduce the ground disturbance substantially to levels closer to those for elephant skidding.

Appendix

Figure S 2-1 An Elephant used in skidding

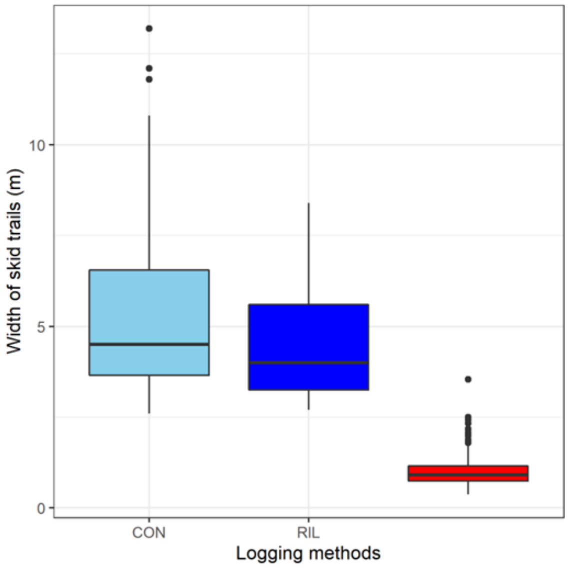

Figure S 2-2 Skid trail width

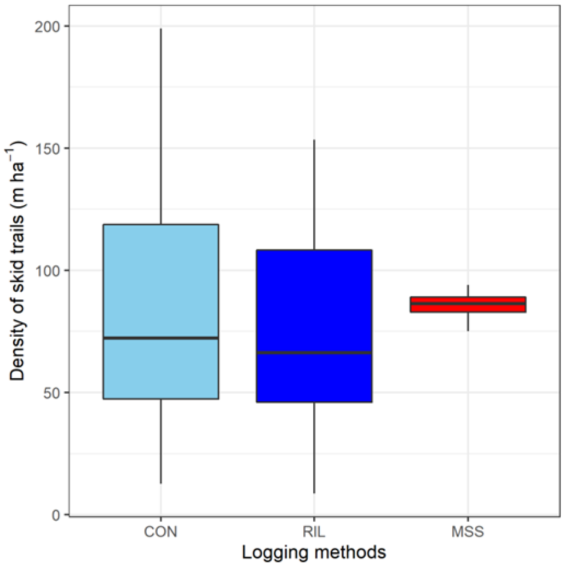

Figure S 2-3 Density of skid trail

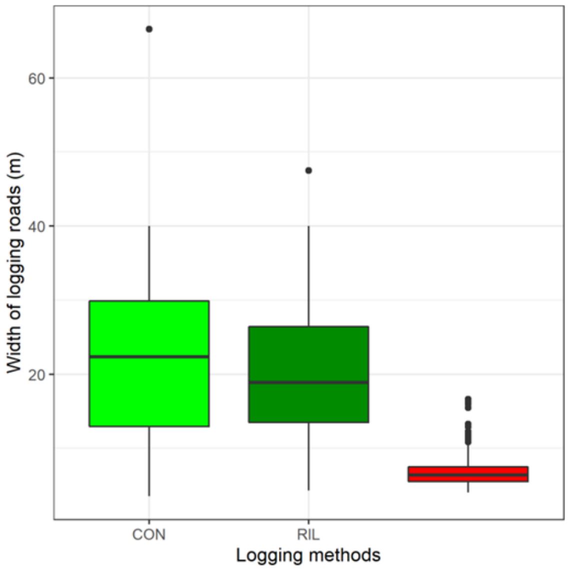

Figure S 2-4 Logging road width

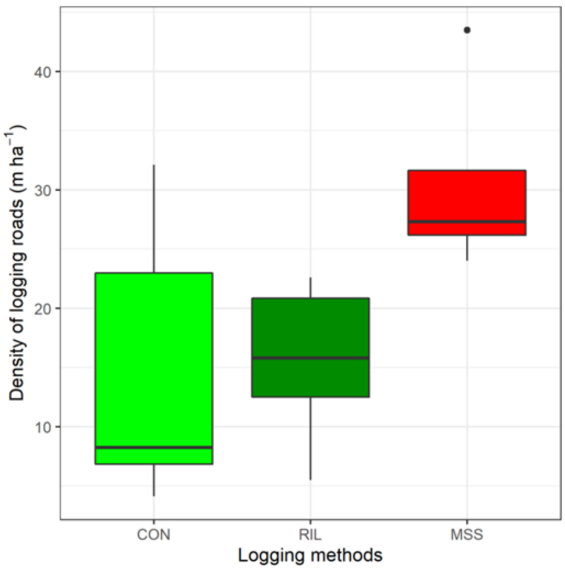

Figure S 2-5 Density of logging road

Table S 2-1 Ground disturbance (%) and harvesting intensity in terms of tree number (trees ha-1) and/or stem volume (m3 ha-1) from the 17 references

No.	References	Conventional logging									Reduce-impact logging									References
		Harvesting intensity		Ground disturbance (%)					Sampling		Harvesting intensity		Ground disturbance (%)					Sampling		
		Tree number (trees ha^{-1})	Volume (m^3 ha^{-1})	Total	Skidd trails	Logging roads	Log landings	Machine manuevering	Area (ha)	Methods	Tree number (trees ha^{-1})	Volume (m^3 ha^{-1})	Total	Skidd trails	Logging roads	Log landings	Machine manuevering	Area (ha)	Methods	
1	Asner *et al.* 2004	2.6		10.5	8.8	1.1	0.6		72	100% inventory	3.8		8.6	6.5	1.7	0.4		379	100% inventory	Asner, G.P., Keller, M., Silva, J.N.M., 2004. Spatial and temporal dynamics of forest canopy gaps following selective logging in the eastern Amazon. Glob. Chang. Biol. 10, 765–783.
		3.1		15.3	12.2	1.5	1.6		39		2.9		5.2	3.7	1.1	0.4		453		
2	Feldpausch *et al*. 2005										2.6	15.0	7.8	5.6	2.0	0.2		1397	Transect (skid trails), 100% invntory (roads, log landings)	Feldpausch, T.R., Jirka, S., Passos, C.A.M., Jasper, F., Riha, S.J., 2005. When big trees fall: Damage and carbon export by reduced impact logging in southern Amazonia. For. Ecol. Manage. 219, 199–215.
											1.1	6.4	6.9	4.2	2.5	0.2		1037		
3	Gullison and Hardner 1993	0.1		3.9	1.87	2.05			602	100% inventory										Gullison, R.E., Hardner, J.J., 1993. The effects of road design and harvest intensity on forest damage caused by selection logging: empirical results and a simulation model from the Bosque Chimanes Bolivia. For. Ecol. Manage. 59, 1–14.
4	Hendrison 1990	5.2		14.5	14.5				20	100% inventory	6.5		7.3	7.3				10	100% inventory	Hendrison, J., 1990. Damage-Controlled Logging in Managed Tropical Rain Forest in Suriname. Ecology and Management of Tropical Rain Forests in Suriname: 4. Wageningen Agricultural University, The Netherlands.
		6.1		16.0	16.0				20		5.7		7.2	7.2				10		
											7.3		7.0	7.0				10		
											7.4		6.8	6.8				10		
											4.7		5.4	5.4				20		
											3.4		5.7	5.7				10		
5	Jackson *et al.* 2002										4.4	12.1	25.0	19.8	2.1	0.1	3.0	852	Transect (skid), 100% inventory (road, landing)	Jackson, S.M., Fredericksen, T.S., Malcolm, J.R. 2002. Area disturbed and residual stand damage following logging in a Bolivian tropical forest. For. Ecol. Manage. 166(1-3), 271-283.
6	Johns *et al.* 1996	5.6	30.0	15.0	7.56	3.36	1.5	2.5	75	100% inventory	4.5	37.0	7.7	4.7	2.0	0.6	0.5	84	100% inventory	Johns, J.S., Barreto, P., Uhl, C., 1996. Logging damage during planned and unplanned logging operations in the eastern Amazon. For. Ecol. Manage. 89, 59–77.
											4.5	37.0	9.5	6.6	2.0	0.6	0.2	21		
7	Jonkers 1987	3.5	15.0	6.0	6.0				20	100% inventory in nine 2.25-ha plots										Jonkers, W.B.J., 1987. Vegetation Structure, Logging Damage and Silviculture in a Tropical Rain Forest in Suriname. Ecology and Management of Tropical Rain Forests in Suriname: 3. Wageningen Agricultural University, The Netherlands.
		6.1	23.0	9.8	9.8				20											
		11.7	46.0	16.7	16.7				20											
8	Medjibe *et al.* 2011										0.8	8.1	5.4	2.8			2.6	50	100% inventory	Medjibe, V.P., Putz, F.E., Starkey, M.P., Ndouna, A.A., Memiaghe, H.R., 2011. Impacts of selective logging on above-ground forest biomass in the Monts de Cristal in Gabon. For. Ecol. Manage. 262, 1799–1806.
9	Medjibe *et al.* 2013	0.8	11.4	10.0	4.5	5.4	0.1		200	100% inventory	0.4	5.7	3.2	1.6	1.5	0.1		508	100% inventory	Medjibe, V.P., Putz, F.E., Romero, C., 2013. Certified and uncertified logging concessions compared in Gabon: Changes in stand structure, tree species, and biomass. Environ. Manage. 51, 524–540.
10	Neba *et al.* 2014	0.8		1.9		1.8	0.1		4400	100% inventory										Neba, S.G., Kanninen, M., Atyi, R.E.A., Sonwa, D.J. 2014. Assessment and prediction of above-ground biomass in selectively logged forest concessions using field measurements and remote sensing data: Case study in South East Cameroon. For. Ecol. Manage. 329, 177-185.
11	Pereira *et al.* 2002	3.7	23.3	8.9	6.8	1.2	0.9		112	100% inventory	3.0	23.2	4.8	3.6	0.6	0.6		108	100% inventory	Pereira, R., Zweede, J., Asner, G.P., Keller, M., 2002. Forest canopy damage and recovery in reduced-impact and conventional selective logging in eastern Para, Brazil. For. Ecol. Manage. 168, 77–89.
		6.4		8.9	7.3	2.0	1.0		14		3.5	23.0	4.6	2.9	1.0	0.7		57	100% inventory	
12	Uhl and Vieira 1989	4.3	31.0	8.9	4.0	4.0			52	100% inventory (roads+skid trails)										Uhl, C., Vieira, I.C.G. 1989. Ecological impacts of selective logging in the Brazilian Amazon: a case study from the Paragominas region of the state of Pará. Biotropica, 98-106.
13	Van der Hout 1999	8.0	25.1	8.9	8.2			4.7	2.0	100% inventory	4.0	16.3	5.0	4.9			0.1	2.0	100% inventory	Van der Hout, P. 1999. Reduced Impact Logging in the Tropical Rain Forest of Guyana: Ecological, Economic, and Silvicultural Consequences. Tropenbos- Guyana Series, 6, Wageningen, The Netherlands.
		16.0	50.1	8.9	9.9			10.8	2.0		8.0	26.5	8.0	7.6			0.4	2.0		
											16.0	47.9	8.8	8.3			0.5	2.0		
14	Verissimo *et al.* 1995	0.3	1.3	5.0	2.3	2.6			166	100% inventory										Veríssimo, A., Barreto, P., Tarifa, R., Uhl, C., 1995. Extraction of a high-value natural resource in Amazonia: the case of mahogany. For. Ecol. Manage. 72, 39–60
		0.5	2.5	5.3	2.3	3.0			114											
		2.1	11.4	10.8	5.2	5.7			74											
15	Webb 1997								28		6.3	45.3	4.0	4.0				28.0	100% inventory	Webb, E.L. 1997. Canopy removal and residual stand damage during controlled selective logging in lowland swamp forest of northeast Costa Rica. For. Ecol. Manage. 95, 117-129.
16	White 1994	2.0		11.4	5.0	6.4				Transect										White, L.J.T., 1994. The effects of commercial mechanised selective logging on a transect in lowland rainforest in the Lope Reserve, Gabon. J. Trop. Ecol. 10, 313–322.
17	Whitman *et al.* 1997	0.5		3.8	3.8				92	100% inventory										Whitman, A.A., Brokaw, N.V.L., Hagan, J.M., 1997. Forest damage caused by selection logging of mahogany (Swietenia macrophylla) in northern Belize. For. Ecol. Manage. 92, 87–96.
	Average	4.2	22.5	9.5	7.6	3.1	0.8	6.0			4.8	23.3	7.3	6.0	1.7	0.4	1.0			

Table S 2-2 Ground disturbance (%) and harvesting intensity (m3 ha-1) based on the data compiled by Ellis et al (2019)

	Sample Block Code	Region	Certification	Area of sample block	Harvest Intensity	Ground disturbance area	Ground disturbance area	Skid trail density	Mean skid trail width	Skid trail area	Road density	Mean road width	Logging road area	Emissions from construction of log landing per ha	Biomass density of adjacent unlogged forest block	Log landing area	Equipment used for skidding operations
				ha	m^3 ha^{-1}	m^2 ha^{-1}	%	m ha^{-1}	m	m^2 ha^{-1}	m ha^{-1}	m	m2 ha-1	MgC ha^{-1}	MgC ha^{-1}	m2 ha-1	
1	DRC2	DRC	none	77.3	3.2	324.9	3.2	24.8	3.9	96.3	8.2	22.7	185.8	0.6	145.2	42.7	skidder
2	DRC4	DRC	none	61.3	9.5	582.8	5.8	72.5	4.2	302.5	8.2	32.0	261.8	0.5	256.4	18.4	skidder
3	DRC6	DRC	none	58.4	6.6	375.4	3.8	54.0	3.9	208.9	8.2	20.0	163.3	0.1	286.1	3.2	skidder
4	DRC1	DRC	none	55.3	11.2	592.6	5.9	85.6	3.9	336.8	8.2	29.0	237.0	0.4	195.7	18.8	skidder
5	DRC3	DRC	none	72.1	8.3	471.5	4.7	66.2	3.8	249.3	8.2	26.2	214.0	0.2	251.6	8.2	skidder
6	DRC5	DRC	none	126.3	6.6	279.8	2.8	39.4	3.0	119.5	8.2	18.5	151.0	0.1	152.6	9.3	skidder
7	DRC8	DRC	none	117.7	6.2	175.7	1.8	12.7	4.1	51.9	8.2	14.3	117.3	0.1	153.5	6.5	skidder
8	DRC7	DRC	none	54.7	12.9	456.3	4.6	69.7	3.4	234.7	8.2	24.1	197.4	0.4	175.7	24.3	skidder
9	GAB9	Gabon	FSC	48.5	4.8	924.0	9.2	69.2	5.0	347.1	20.2	24.9	503.6	1.5	202.1	73.2	bulldozer
10	GAB6	Gabon	none	297.3	3.3	714.8	7.1	18.4	4.5	83.4	20.2	30.2	611.2	0.4	202.1	20.2	bulldozer
11	GAB2	Gabon	none	52.6	5.1	920.4	9.2	54.7	6.7	365.2	20.2	22.0	445.3	2.2	202.1	109.9	bulldozer
12	GAB1	Gabon	none	50.2	6.3	793.3	7.9	43.7	5.1	225.0	20.2	26.1	528.4	0.8	202.1	39.9	bulldozer
13	GAB8	Gabon	none	50.3	16.5	627.0	6.3	30.5	6.5	198.4	20.2	15.9	322.5	2.1	202.1	106.0	bulldozer
14	GAB3	Gabon	none	201.5	9.6	828.7	8.3	23.1	6.6	152.8	20.2	31.7	640.8	0.7	202.1	35.1	bulldozer
15	GAB5	Gabon	FSC	48.0	20.5	980.0	9.8	58.6	5.8	342.6	20.2	28.9	584.8	1.1	202.1	52.7	bulldozer
16	GAB4	Gabon	FSC	100.6	10.8	540.6	5.4	34.3	5.3	182.5	20.2	13.5	274.0	1.7	202.1	84.1	bulldozer
17	GAB7	Gabon	none	58.7	18.0	817.8	8.2	43.2	6.4	278.1	20.2	23.2	469.3	1.4	202.1	70.4	bulldozer
18	RoC5	RoC	FSC	57.3	7.3	967.9	9.7	50.3	3.9	197.0	15.8	47.5	750.2	0.4	202.1	20.7	skidder
19	RoC3	RoC	none	53.0	13.4	839.3	8.4	70.7	3.4	242.9	15.8	35.6	562.0	0.7	202.1	34.4	skidder
20	RoC1	RoC	none	55.8	15.1	882.5	8.8	70.0	3.2	221.1	15.8	38.0	600.8	1.2	202.1	60.7	skidder
21	RoC4	RoC	FSC	52.6	10.7	490.7	4.9	40.1	2.7	108.4	15.8	22.5	355.8	0.5	202.1	26.5	skidder
22	RoC2	RoC	FSC	38.3	16.5	796.4	8.0	58.1	4.1	240.9	15.8	33.8	533.3	0.5	202.1	22.3	skidder
23	RoC6	RoC	none	53.2	41.3	773.9	7.7	60.4	4.5	273.5	15.8	31.5	497.6	0.1	202.1	2.9	skidder
24	A	EKal	FSC	343.6	17.2	1581.3	15.8	132.1	8.4	1103.9	11.8	40.0	470.8	0.2	230.4	6.6	bulldozer
25	D	EKal	none	159.3	10.1	707.8	7.1	45.2	9.2	415.0	11.8	24.5	288.4	0.1	221.8	4.4	bulldozer
26	C	EKal	none	107.3	21.3	1655.5	16.6	109.0	12.1	1322.6	11.8	25.2	297.0	0.8	220.3	35.8	bulldozer
27	Ba	EKal	FSC	50.5	47.5	1264.3	12.6	129.2	7.1	918.5	11.8	26.4	310.4	0.8	230.4	35.4	bulldozer

	Sample Block Code	Region	Certif icatio n	Area of sample block	Harvest Intensity	Groun d disturb ance area	Groun d disturb ance area	Skid trail density	Mean skid trail width	Skid trail area	Road density	Mean road width	Logging road area	Emissions from constructio n of log landing per ha	Biomass density of adjacent unlogged forest block	Log landing area	Equipmen t used for skidding operations
				ha	$m^3 ha^{-1}$	$m^2 ha^{-1}$	%	$m ha^{-1}$	m	$m^2 ha^{-1}$	$m ha^{-1}$	m	m2 ha-1	$MgC ha^{-1}$	$MgC ha^{-1}$	m2 ha-1	
28	G	EKal	none	98.0	47.4	2334.7	23.3	189.8	9.7	1838.3	11.8	40.0	471.0	0.7	259.1	25.4	bulldozer
29	Bb	EKal	FSC	90.6	48.2	1064.3	10.6	106.1	7.1	754.1	11.8	24.5	287.8	0.6	257.0	22.3	bulldozer
30	I	EKal	none	107.0	56.5	2014.7	20.1	132.1	11.8	1554.2	11.8	37.3	438.6	0.5	230.4	21.8	bulldozer
31	E	EKal	none	73.0	35.5	1872.0	18.7	132.1	10.8	1421.4	11.8	35.0	412.5	0.9	230.4	38.1	bulldozer
32	H	EKal	none	86.3	27.6	1229.2	12.3	87.5	10.0	871.0	11.8	28.7	337.2	0.5	222.6	21.0	bulldozer
33	F	EKal	none	55.2	53.3	1450.7	14.5	132.1	7.7	1022.3	11.8	32.9	387.5	0.9	230.4	40.9	bulldozer
34	Xmaben	YucP	none	408.9	0.3	85.4	0.9	15.1	3.7	56.5	6.0	3.6	21.9	0.1	88.7	7.0	tree farmer
35	FCarilloP	YucP	none	239.8	1.2	293.2	2.9	68.3	3.9	263.4	6.0	4.1	24.7	0.0	95.0	5.1	tree farmer
36	Naranjal	YucP	none	116.5	2.5	383.1	3.8	78.2	4.3	336.4	6.0	5.1	31.0	0.1	83.0	15.7	tree farmer
37	Petcacab	YucP	none	170.2	4.6	468.8	4.7	112.0	3.6	407.6	6.0	3.5	21.1	0.3	76.8	40.1	tree farmer
38	StaMaria P	YucP	none	124.3	3.6	400.4	4.0	85.0	3.9	332.2	6.0	3.8	23.1	0.4	78.6	45.1	tree farmer
39	Caobas	YucP	FSC	1060.0	1.1	55.8	0.6	8.6	3.2	27.5	6.0	4.3	26.0	0.0	76.6	2.3	tractor
40	Botes	YucP	none	308.4	1.2	146.2	1.5	33.3	3.3	109.3	6.0	5.5	33.0	0.0	73.0	3.9	tractor
41	Noh-Bec	YucP	FSC	181.5	6.8	528.8	5.3	114.6	3.9	447.6	6.0	4.8	28.7	0.3	64.2	52.5	tree farmer
42	Guadalaj ara	YucP	none	270.4	3.6	196.5	2.0	62.8	2.7	167.9	6.0	3.8	22.6	0.0	53.9	6.0	tractor
43	P-4a	MdD	none	22.0	5.6	421.9	4.2	124.5	3.0	373.6	4.1	8.1	33.2	0.1	62.3	15.1	skidder
44	P-5b	MdD	FSC	65.3	5.0	246.2	2.5	56.2	3.0	168.5	4.1	16.3	66.3	0.1	62.3	11.4	skidder
45	P-6a	MdD	FSC	97.4	2.9	218.2	2.2	42.5	3.0	127.4	4.1	20.6	84.1	0.0	62.3	6.6	skidder
46	P-6b	MdD	FSC	86.4	5.5	340.0	3.4	86.5	3.0	259.5	4.1	19.7	80.2	0.0	62.3	0.3	skidder
47	P-1	MdD	FSC	115.2	3.7	206.3	2.1	47.3	3.0	141.9	4.1	15.2	62.1	0.0	62.3	2.3	bulldozer
48	P-3	MdD	none	55.5	5.7	321.0	3.2	72.0	3.0	216.1	4.1	25.1	102.1	0.0	62.3	2.8	skidder
49	P-4b	MdD	none	40.9	8.1	245.1	2.5	65.2	3.0	195.5	4.1	10.4	42.3	0.0	62.3	7.2	skidder
50	P-5a	MdD	FSC	95.0	3.2	157.8	1.6	28.2	3.0	84.5	4.1	17.7	72.3	0.0	62.3	1.0	skidder
51	P-2	MdD	none	38.0	7.2	270.3	2.7	77.0	3.0	231.0	4.1	7.2	29.5	0.1	62.3	9.7	skidder

	Sample Block Code	Region	Certification	Area of sample block	Harvest Intensity	Ground disturbance area	Ground disturbance area	Skid trail density	Mean skid trail width	Skid trail area	Road density	Mean road width	Logging road area	Emissions from construction of log landing per ha	Biomass density of adjacent unlogged forest block	Log landing area	Equipment used for skidding operations
				ha	$m^3\ ha^{-1}$	$m^2\ ha^{-1}$	%	$m\ ha^{-1}$	m	$m^2\ ha^{-1}$	$m\ ha^{-1}$	m	m2 ha-1	$MgC\ ha^{-1}$	$MgC\ ha^{-1}$	m2 ha-1	
52	C4	Suriname	none	79.4	3.6	692.3	6.9	89.4	6.0	539.3	6.4	20.5	131.1	0.6	292.7	21.9	excavator
53	C3	Suriname	none	52.3	6.8	1021.8	10.2	136.8	6.4	872.0	6.4	21.2	135.4	0.4	281.2	14.4	excavator
54	P3	Suriname	none	48.2	8.4	973.6	9.7	114.8	7.1	810.6	6.4	15.9	101.2	1.8	291.9	61.8	excavator
55	C2	Suriname	none	49.2	10.2	763.9	7.6	98.3	5.6	552.9	6.4	31.4	200.6	0.2	220.1	10.4	excavator
56	P4	Suriname	none	49.0	10.1	851.4	8.5	136.7	4.9	673.9	6.4	19.1	122.0	1.1	201.3	55.5	excavator
57	P2	Suriname	none	49.3	16.5	881.7	8.8	162.9	4.3	698.9	6.4	11.5	73.5	3.2	288.0	109.4	excavator
58	PFSC2	Suriname	FSC	50.0	17.0	1050.4	10.5	124.1	7.2	887.3	6.4	14.0	89.2	1.5	202.5	74.0	skidder
59	PFSC1	Suriname	FSC	101.1	10.0	613.8	6.1	96.7	5.0	485.5	6.4	14.3	91.5	0.7	200.2	36.7	skidder
60	P1	Suriname	none	49.4	16.5	856.7	8.6	137.6	5.0	690.1	6.4	14.7	94.0	1.5	202.9	72.6	skidder
61	C1	Suriname	none	50.3	11.3	872.4	8.7	116.9	5.7	666.2	6.4	25.5	162.4	0.8	188.3	43.8	bulldozer

Table S 2-3 Widths and density of skid trails and logging loads reported in 16 references

No.	References	Skid trails: Conventional logging (CON) Width (m)	Skid trails: Conventional logging (CON) Density (m ha^{-1})	Skid trails: Reduced-impact logging (RIL) Width (m)	Skid trails: Reduced-impact logging (RIL) Density (m ha^{-1})	Logging roads: Conventional logging (CON) Width (m)	Logging roads: Conventional logging (CON) Density (m ha^{-1})	Logging roads: Reduced-impact logging (RIL) Width (m)	Logging roads: Reduced-impact logging (RIL) Density (m ha^{-1})	Remarks	References
1	Bryan et al. (2016)							39.3	13.2		Bryan J, Shearman P, Ash J, Kirrpatrick JB. 2010. Impact of logging on aboveground biomass stocks in lowland rain forest , Papua New Guinea. Ecol Appl. 20:2096–2103.
2	Feldpausch et al. (2005)			4.0				10.6	21.5		Feldpausch TR, Jirka S, Passos CAM, Jasper F, Riha SJ. 2005. When big trees fall: Damage and carbon export by reduced impact logging in southern Amazonia. For Ecol Manage. 219:199-215.
3	Griscom et al. (2014)	10.6	156.3	7.7	116.1	31.8		32.8		RIL values were averages of three FSC sites, and CON values were averages of six Non-FSC sites.	Griscom B, Ellis P, Putz FE. 2014. Carbon emissions performance of commercial logging in East Kalimantan, Indonesia. Glob Chang Biol. 20:923–937.
4	Gullison and Hardner (1993)	13.2	14.2			24.7	8.3				Gullison RE, Hardner JJ. 1993. The effects of road design and harvest intensity on forest damage caused by selective logging: empirical results and a simulation model from the Bosque Chimanes, Bolivia. For Ecol Manage. 59:1–14.
5	Iskandar et al. (2006)		48.0				28.6			Average of five 20-ha sample areas	Iskandar H, Snook LK, Toma T, MacDicken KG, Kanninen M. 2006. A comparison of damage due to logging under different forms of resource access in East Kalimantan, Indonesia. For Ecol Manage. 237:83–93.
6	Jackson et al. (2002)			3.5				11.3			Jackson SM, Fredericksen TS, Malcolm JR. 2002. Area disturbed and residual stand damage following logging in a Bolivian tropical forest. For Ecol Manage. 166:271–283.
7	Johns et al. (1996)	3.9	193.8	3.3	153.4	12.3	27.3	9.0	22.6	RIL values were averages of two sites.	Johns JS, Barreto P, Uhl C. 1996. Logging damage during planned and unplanned logging operations in the eastern Amazon. For Ecol Manage. 89:59–77.
8	Karsten et al. (2014)			4.0				8.0			Karsten RJ, Meilby H, Larsen JB. 2014. Regeneration and management of lesser known timber species in the Peruvian Amazon following disturbance by logging. For Ecol Manage. 327:76–85.
9	Medjibe et al. (2011)			4.1	69.0						Medjibe VP, Putz FE, Starkey MP, Ndouna AA, Memiaghe HR. 2011. Impacts of selective logging on above-ground forest biomass in the Monts de Cristal in Gabon. For Ecol Manage. 262:1799–1806.
10	Medjibe et al. (2013)	5.3	28.7	3.8	15.2	66.6	8.1	18.9	5.5		Medjibe VP, Putz FE, Romero C. 2013. Certified and uncertified logging concessions compared in Gabon: Changes in stand structure, tree species, and biomass. Environ Manage. 51:524–540.
11	Neba et al. (2014)					20.0	10.0				Neba GS, Kanninen M, Eba'a Atyi R, Sonwa DJ. 2014. Assessment and prediction of above-ground biomass in selectively logged forest concessions using field measurements and remote sensing data: Case study in South East Cameroon. For Ecol Manage. 329:177–185.
12	Pinard et al. (2000)	5.1	199.0	5.4	66.5					Average of four areas	Pinard MA, Barker MG, Tay J. 2000. Soil disturbance and post-logging forest recovery on bulldozer paths in Sabah, Malaysia. For Ecol Manage. 130:213–225.
13	Sist et al. (2003)	7.7	70.9	5.9	65.9						Sist P, Sheil D, Kartawinata K, Priyadi H. 2003. Reduced-impact logging in Indonesian Borneo: Some results confirming the need for new silvicultural prescriptions. For Ecol Manage. 179:415–427.
14	Uhl and Vieira (1989)	2.6	145.4			12.5	32.1			Based on the map and widths of roads, primary roads were regarded as logging roads, and secondary and terriary roads were as skid trails	Uhl C., Vieira ICG. 1989. Ecological impacts of selective logging in the Brazilian Amazon: a case study from the Paragominas region of the state of Pará. Biotropica, 98-106.
15	van der Hoeven et al. (2009)					17.0					Van der Hoeven CA, de Boer WF, Prins HHT. 2009. Roadside conditions as predictor for wildlife crossing probability in a Central African rainforest. Afr J Ecol. 48:368–377.
16	Whitman et al. (1997)	3.6	105.6							Skid tails coverd 3.8% of the logging area. 105.6m =380m^2/3.6m	Whitman AA, Brokaw NVL, Hagan JM. 1997. Forest damage caused by selection logging of mahogany (Swietenia macrophylla) in northern Belize. For Ecol Manage. 92:87–96.
	Average	6.5	106.9	4.6	81.0	26.4	19.1	18.5	15.7		
	n	8	9	9	6	7	6	7	4		

Table S 2-4 GLM results using ground disturbance along elephant skid trails (%) and harvesting intensity in stem volume (SV m3 ha-1) or number of trees (TN trees ha-1) for each of 45 elephant skid trail networks in Myanmar (Figure 3)

Response variable	Explanatory variable	Estimate	Std. Error	t value	Pr (>|t|)
Ground disturbance along skid trails (%)	(Intercept)	-1.7087	0.2653	-6.441	<0.0001
	Log (stem volume of harvested trees per ha)	0.9777	0.1256	7.782	<0.0001
Ground disturbance along skid trails (%)	(Intercept)	-0.8683	0.1182	-7.344	<0.0001
	Log (number of harvested trees per ha)	1.147	0.1032	11.119	<0.0001

Table S 2-5 GLM results for ground disturbance (%) using logging methods (CON, RIL and MSS) and havesting intensity in terms of stem volume (m3 ha-1) and number (trees ha-1) of harvested trees

	Case of using stem volume of harvested trees (m^3 ha^{-1}) as harvesting intensity					Case of using number of harvested trees (trees ha^{-1}) as harvesting intensity				
Response variable	Explanatory variable	Estimate	Std. Error	t value	Pr(>|t|)	Explanatory variable	Estimate	Std. Error	t value	Pr(>|t|)
Ground disturbance along skid trails (%)	(Intercept)	-0.011	0.171	-0.064	0.949	(Intercept)	1.334	0.147	9.088	<0.0001
	Log (stem volume of harvested trees per ha)	0.666	0.064	10.488	<0.0001	Log (number of harvested trees per ha)	0.677	0.070	9.715	<0.0001
	Logging method (MSS)	-1.056	0.140	-7.534	<0.0001	Logging method (MSS)	-1.728	0.158	-10.912	<0.0001
	Logging method (RIL)	-0.224	0.156	-1.440	0.152	Logging method (RIL)	-0.462	0.186	-2.481	0.015
Ground disturbance along logging roads (%)	(Intercept)	-0.044	0.240	-0.182	0.856	(Intercept)	1.126	0.140	8.038	<0.0001
	Log (stem volume of harvested trees per ha)	0.419	0.097	4.332	<0.0001	Log (number of harvested trees per ha)	0.002	0.098	0.024	0.981
	Logging method (MSS)	0.105	0.440	0.240	0.811	Logging method (MSS)	-0.397	0.277	-1.432	0.166
	Logging method (RIL)	-0.116	0.206	-0.564	0.574	Logging method (RIL)	-0.627	0.210	-2.979	0.007
Ground disturbance along logging landings (%)	(Intercept)	-2.237	0.268	-8.348	<0.0001	(Intercept)	-1.297	0.240	-5.397	<0.0001
	Log (stem volume of harvested trees per ha)	0.506	0.107	4.736	<0.0001	Log (number of harvested trees per ha)	0.875	0.159	5.506	<0.0001
	Logging method (MSS)	0.615	0.537	1.146	0.256	Logging method (MSS)	0.147	0.355	0.413	0.685
	Logging method (RIL)	-0.189	0.220	-0.859	0.393	Logging method (RIL)	-0.543	0.247	-2.202	0.043

CHAPTER III

Modeling-based approach to estimate residual tree damage along elephant skid trails, logging roads and log landings under the Myanmar Selection System

3.1 Introduction

There have been growing attentions on conservation values of selectively logged production forests in tropics in terms of various ecosystem services including wood production (Berry et al., 2008; Putz et al., 2012). Thus, it is still crucial to improve management strategies through effectively implementing reduced-impact logging (RIL) in order to enhance the conservation values in tropical forests (Bicknell et al., 2014, Runting et al., 2019). RIL can be defined as intensively planned and carefully controlled timber harvesting by trained workers, which includes a pre-harvest inventory, marking of trees to be felled, skid trail planning, pre-harvest liana cutting and directional felling . Quantifying damage levels to residual stands is the fundamental to evaluate effectiveness and improvement of RIL operations.

Many studies for evaluating residual tree damage, mostly adopted an area-based approach where percentages of residual tree damage are evaluated at a large area. Such an area-based empirical approach is helpful to get average values at the stand level, but it is difficult to incorporate various conditions such as size of felled and residual trees and felling intensity, which likely influence residual stand damage. In contrast, a modelling and tree-based approach is useful for more mechanistic consideration (Picard et al., 2012). Chheng et al., (2015) developed multinomial logistic models to predict probability of a residual tree sustaining severe, slight or no damage caused by tree felling in tropical semi-evergreen forests of Cambodia, with using the size of felled and residual trees as the explanatory variables. Khai et al., (2017) applied this proposed tree-based approach to evaluate felling damage in a tropical mixed deciduous forest of Myanmar and confirmed that this approach is useful to compare residual tree damage under different stand structure and site condition. Thus such a modelling approach has potentials to be used to evaluate effectiveness of improving various logging operations. However, no study has tried a modelling-based approach for estimating residual tree damage caused by operations other than felling, such as skidding and operations along logging roads and log landings.

Myanmar has the oldest tradition of selective logging, so-called Myanmar Selection System (MSS) in natural forests, with the main target species being teak (*Tectona grandis*).

The specific feature of the MSS is still using elephants for skidding. The long history of MSS using elephants gives us an impression that the MSS may be a good practice of tropical selective logging (Khai et al., 2016b), but on the other hand, studies have indicated forest degradation extensively happening in the production forests managed under the MSS (Mon et al.,2012, Win et al.,2012, Win et al.,2018). Such discrepancy between thoughts and realities led a research team of Kyushu University in Japan to evaluate where problems exist among the MSS operations and how to improve the operations and to ensure sustainability of the MSS. So far, the team has indicated that ground disturbance by elephant skidding is the lowest level as compared to that by machine skidding in the other countries (Khai et al., 2016; Minn et al., 2022), and the probability of residual tree damage is relatively similar to one found in Cambodia by Chheng et al., (2015), who showed that the relationship between percentages of residual tree damage and felling intensity was quite similar between two cases in Cambodia and Indonesia. However, levels of residual tree damage caused by operations other than tree felling are still unknown in Myanmar.

The objective of this chapter is to estimate residual tree damage caused by elephant skidding and operations at logging roads and log landings in Myanmar, through a modelling-based approach. First, we used a multinomial logistic model to predict the effect of residual tree size on a probability of a residual tree sustaining severe, slight or no damage along logging roads, log landing and elephant skid trails. Second, we used the estimated model parameters to simulate residual tree damage percentages at the 1.0 ha unit area in relation to felling intensity (trees ha^{-1}). Finally, we compared levels of residual tree damage caused by different operations (felling, skidding and operations in logging road and log landing) among the MSS and the other countries' cases.

3.2 Materials and Methods

3.2.1 Study sites

As in our previous study (Minn et al., 2022), we conducted surveys at two sites; a site in Bago, which is the legendary birthplace of the Myanmar Selection System (MSS), and a site in Katha, a famous northern logging concession region (Figure 3-1). The Bago and Katha sites are respectively located at 17° 40' N, 96° 0' E and 23° 53' N, 95° 58' E. The mean annual rainfalls and temperatures are respectively 3089 and 1532 mm and 26.7 and 25.1 °C. At each site, we surveyed two compartments (namely 29C and 14C in Bago and 45C and 46C in Katha). General information is provided for each compartment in Table 3-1. The latest logging operations were conducted in two successive logging seasons spanning 2014 to 2016 in 29 C and 14C of Bago and in the single 2017–2018 logging season in 45C and 46C of Katha. The recorded history of official logging in the last 10 years was not available for any the compartment before the latest logging. Two governmental extraction agencies, namely Bogo South and Katha East agencies, conducted logging operations in each area.

Trees to be felled were formerly selected by assigned Forest Department officials. The minimum DBH of trees was determined as 58.2 cm (local limit of 6 ft. in girth). Trees were felled and cut into logs by trained operators using chainsaws. Logs were then collected and dragged to log landings by trained operators using elephants. The log landings and logging roads were constructed using bulldozers (D65). Trucks finally transported the logs to sawmills or more accessible depots.

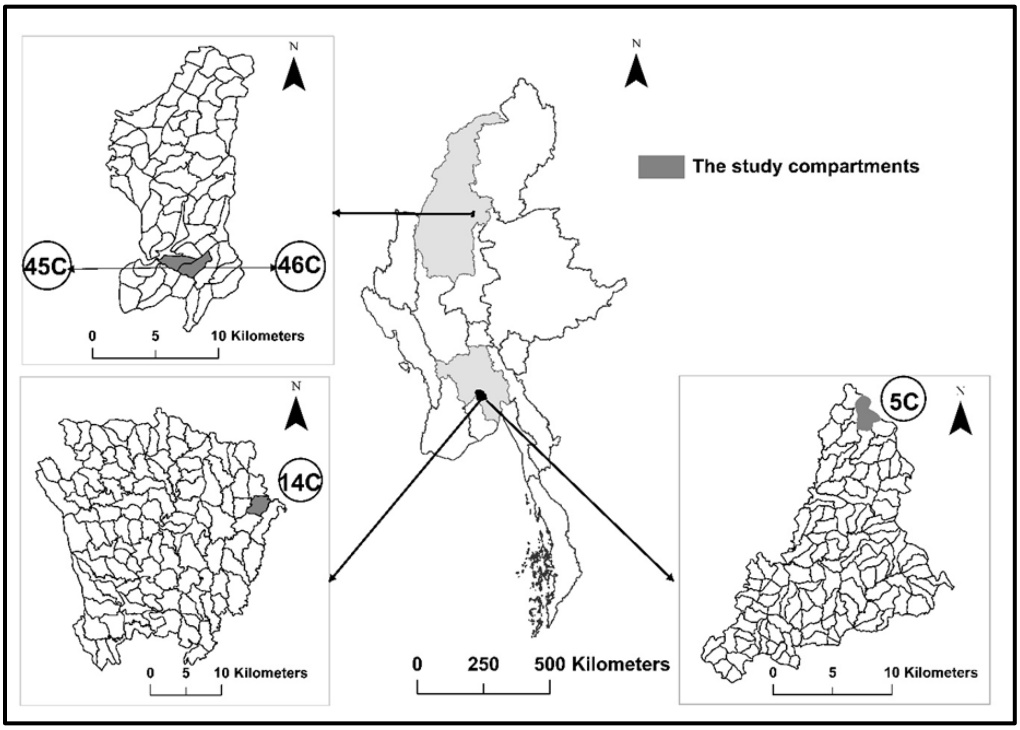

Figure 3-1 Locations of surveyed compartments; 5C and 14C in two reserved forests of the southern region of Bago and 45C and 46C in one reserved forest of the northern region of Katha in Myanmar

Table 3-1 General information of the study compartments

Region	Bago area		Katha area	
Reserved Forest	Shwelaung Kodukwe	(2) South Zama ye	Pyinde	Pyinde
Compartment	5C	14C	45C	46C
Whole area (ha)	280	622	176	213
Operational area (ha)	280	207	136	213
Soil types	Fluvisols	Fluvisols	Lithosols	Lithosols
Logging intensity				
Tree number (trees ha^{-1})	1.6	2.1	1.1	1.5
Log volume (m^3 ha^{-1})	5.4	4.3	4.9	5.0

3.2.2 Field measurements

I measured residual tree damage along three operational areas, which are elephant skid trails, logging roads and log landings. For these measurements, we delineated areas within 3 m distance from the edges of these operational areas (Figure 3-2). In all of four compartments (Figure 3-1), we measured residual tree damage along the skid trails at the same time when I measured soil disturbance area (Minn et al., 2022) just after elephant skidding operations but before the construction of logging roads and log landing construction.

I visited again to the study sites when constructions of logging roads and log landings were finished and measured residual tree damage while measuring soil disturbance at logging roads and log landing. Residual tree damage along logging roads and log landings were measured in three compartments except compartment 29C (Figure 3-2).

As in Chheng et al., (2015) and Khai et al., (2017), the damage classes of each tree were assessed using a method proposed by Johns et al., (1996). In this method, tree damage to crowns and boles, were ranked on a scale from minor to moderate to severe. Crown damage was ranked as severe if more than 66% of the crown was lost, moderate if 33–66% of the crown was lost, and minor if less than 33% of the crown was lost. Similarly, bole damage was ranked as severe when the bole was smashed, uprooted, or broken. Bole damage was ranked as moderate if more than 100 cm^2 of bark was removed, and it was ranked as minor if less than 100 cm^2 of bark was removed.

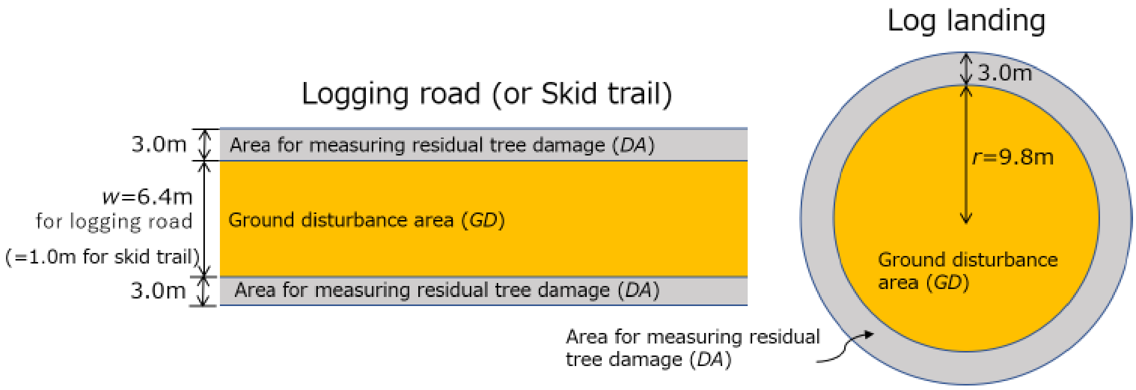

Figure 3-2 Area delineated for measuring residual tree damage (areaj) and ground damage area (gdj) for logging road (skid trail) and log landing

3.2.3 Data analysis

3.2.3.1 Data analysis within the surveyed area scale

Since residual tree damage is usually reported on a 1.0 ha basis, we estimated the probability of a damage class within a 1.0-ha unit. The aforementioned multinomial model predicts the probability $p_{cj}(x_i)$ for ith residual tree with DBH(x_i) to be in a damage class c (severe, slight or no damage) within the area that was delineated with the 3m distance along the edge of the operational places. As described in the previous study (Chheng et al 2015), this probability is influenced by the area delineated for measuring residual tree damage. This is because residual tree damage can occur only near the operational area and the number of trees with "severe" and "slight" damage is the same even when the delineated area expands far from the operational area, whereas the number of "no damage" trees or all the trees increases in the larger area (Chheng et al 2015). Here, we define DA (m^2) as the delineated area within 3m along each operational place in a 1.0-ha unit, and then we estimated the probability to be damage class c (severe or slight) within a 1.0-ha unit as follows.

$$p_c(x_i) \times DA \times 10^{-4} \quad (1)$$

Then, the probability of no damage class within the 1.0-ha unit can be simply described by,

$$1 - p_{severe}(x_i) \times DA \times 10^{-4} - p_{slight}(x_i) \times DA \times 10^{-4} \quad (2)$$

In my previous study, I found that ground disturbance (GD) per ha (m^2 ha^{-1}) along skid trails and log landings was linearly increased with increasing logging intensity (LI, trees ha^{-1}), but GD of logging roads has a constant irrespective of LI as follows.

$GD = \alpha \times LI$ (α = 56.11 for skid trails and 21.98 for log landings) (3)

$GD = \beta$ (β= 210.0 for logging roads) (4)

Using these relations, the delineated area (DA) within 3 m along the ground disturbance areas can be also expressed as linear relations to LI for skid trails and as constant irrespective of LI for logging roads, as follows. For skid trails or logging roads,

$DA = 6.0\,l$ (5)

where l is density (the length per ha; m ha^{-1}) of skid trails or logging roads and 6.0 m is the sum of both side distance 3.0 m from the edges (Figure 3-2). GD can express can be also expressed;

$GD = l \times w$, (6)

where w is average width of skid trails (1.0 m) and logging roads (6.4 m), which were obtained in the previous study (Minn et al 2022). Using Equations (3) or (4), and (6), Equation (5) can be expressed;

$DA = 6.0(\alpha \times LI)/w = 336.7\,LI$ for skid trails (7)

$DA = 6.0\beta/w = 196.9$ for logging roads (8)

To simplify a calculation for log landing, we assume that all the logging landings have the same shape of a circular with the area $gd1$ = 302.84 m^2 (the radius r = 9.82 m), which was obtained as the average area among a total of 79 samples in the previous study (Minn et al 2022). Here, we express

$DA = da1 \times n_l$ (9)

where n_l is the number of log landings per ha and $da1$ is the area delineated with 3m distance from the boundary of an assumed circular log landing (Figure 3-2), where

$da1 = 3\pi(2r+3) = 213.34$ (m^2), (10)

$n_l = GD/gd1 = GD/302.84$. (11)

and then using Equations (3), (10), (11), the Equations (9) for can be expressed

$DA = da1 \times (\alpha \times LI)/a = 15.48LI$ for log landings (12)

Damage data are often reported as a rate (%) of the number of damaged trees in a stand. In the present study, the probability to be damage class c expressed as Equation (1) varies with DBH x_i of the ith residual tree within a 1.0-ha unit. Thus, the mean probability for residual trees provides an estimate of damage rate (DRc) in the 1.0-ha unit area.

$$DR_c(\%) = \frac{1}{n_j}\sum_{i=1}^{n_j}\{p_c(x_i) \times DA \times 10^{-4}\} = \bar{p}_c \times DA \times 10^{-4} \quad (13)$$

where n_j and $\bar{p}_c$ is the observed number of residual trees and average probability to be damage class c (severe or slight) among the residual trees. For the calculation of $\bar{p}_c$, we used

DBH distribution data of residual trees within the area delineated for measuring damage along skid trails (n=1880), logging roads (n=801) and log landing (n=306) (Figure 3.3), resulting in $\bar{p}_c = 0.184267, 0.273111 and\ 0.552678,$ respectively.

Finally, we can express relationships between $DR_c(\%)$ and *LI*;

$$DR_c(\%) = \bar{p}_c \times 0.03367\, LI = 0.62043\, LI \text{ for skid trails} \quad (14)$$

$$DR_c(\%) = \bar{p}_c \times 0.01969 = 0.537756 \text{ for logging roads} \quad (15)$$

$$DR_c(\%) = \bar{p}_c \times 0.001548 LI = 0.08555\, LI \text{ for log landings.} \quad (16)$$

We also estimated $DR_c(\%)$ caused by felling using the method proposed by Chheng et al (2015), as follows. They used the multinomial model to predict the probability $p_c(x_{ij}, y_j)$for *i*th residual tree with DBH x_{ij} to be in a damage class *c* (severe or slight) caused by the *j*th felled tree with DBH y_i within the plot area of 0.1 ha surrounding the *j*th felled tree. Then a linear model was developed to predict the relationship between logging intensity *LI* trees ha^{-1}) and a rate (DR_c % ha^{-1}) of residual trees sustaining damage class *c* (severe or slight) caused by felling;

$$DR_c(\%) = \bar{p}_c(y_j) \times LI, \quad (17)$$

where $\bar{p}_c(y_j)$ is the mean probability caused by one felled tree j within the 1.0-ha unit area and expressed by,

$$\bar{p}_c(y_j) = \frac{1}{n_j}\sum_{i=1}^{n_j} p_c(x_{ij}, y_j) \times 0.1, \quad (18)$$

n_j is the observed number of the residuals trees in the plot laid out the *j*th felled tree. In the present study, we used the estimates of the multinomial model fitted to data from twenty 0.1-ha plots in compartment 29 in the South Zamayae reserved forest (Table 2 in Khai et al. 2017) in Myanmar. As DBH of one felled tree j for the calculation of $p_c(x_{ij}, y_j)$, we used the mean DBH of 205 felled trees ($y_j = 74.3\ cm$), which were skidded through the trails where skidd damage were investigated. The residual tree DBH values (x_{ij}) were given by the values of residual trees sampled along skid trails (n=1888, Figure 3.3). Using these data, we obtained felling damage rate as

$$DR_c(\%) = 1.90570\, LI \quad (19)$$

3.3 Results and discussion

3.3.1 Overview of residual tree damage along each operational area

In the areas delineated within 3 m distance from the edges of each operational area, total damage percentages were the largest in log landings (56.9%), followed by in logging roads (31.2%) and skid trails (19.4%) (Table 3-2). For logging roads and log landing, severe damage rate is higher in smaller trees while slight damage increases for larger trees (Figure 3. 3 and Figure 3. 4), but severe and slight damages show relatively equal rates for a total of pooling all sized trees (Table 3-2). In contrast, for skid trails, only 0.6% of severe damage occurred in only smallest DBH class while slight damage occurred evenly for all DBH classes.

Our field observation during elephant skidding showed that elephants always tried avoiding positions of residual trees during carrying the logs. Such behaviors by elephant may lead the lowest level of severe damage along skid trails. Along log landings and logging roads, residual trees are damaged first when trees are felled down during the construction. Therefore, damage rate patterns along these operational areas over different DBH may be similar to felling damage where it is commonly found that larger damages rates occurs in smaller trees. Even after constructing log landing, residual trees can likely be damaged when elephants move around logs to face the same direction and the machine is used to carry the logs on the trucks, while residual tree damage along logging roads may not often occur when the trucks are used for log transportation. Such operational differences may result in more damage rate along log landing than logging roads.

Table 3-2 Stand information and percentage of damaged trees within 3 m distance from the edges of ground disturbance area in three operational phases

	Operational places		
	Skid trails	Logging roads	Log landings
Surveyed area (ha)	5.0	1.7	1.6
Residual trees			
Number of trees (trees ha^{-1})	358.0	458.0	654.0
Mean DBH (cm)	25.4	25.9	29.0
Basal area ($m^2 ha^{-1}$)	24.2	32.9	56.8
Felled trees			
Mean DBH (cm)	74.3		

Median DBH (cm)	71.1		
Percentage of damaged trees (%)			
Severe damage			
Bole	0.6	17.3	23.8
Crown	0.0	0.8	0.9
Whole	0.6	18.1	24.7
Slight damage			
Bole	17.8	10.0	30.6
Crown	0.0	3.1	1.6
Whole	17.8	13.1	32.2
No damage	81.6	68.8	43.1

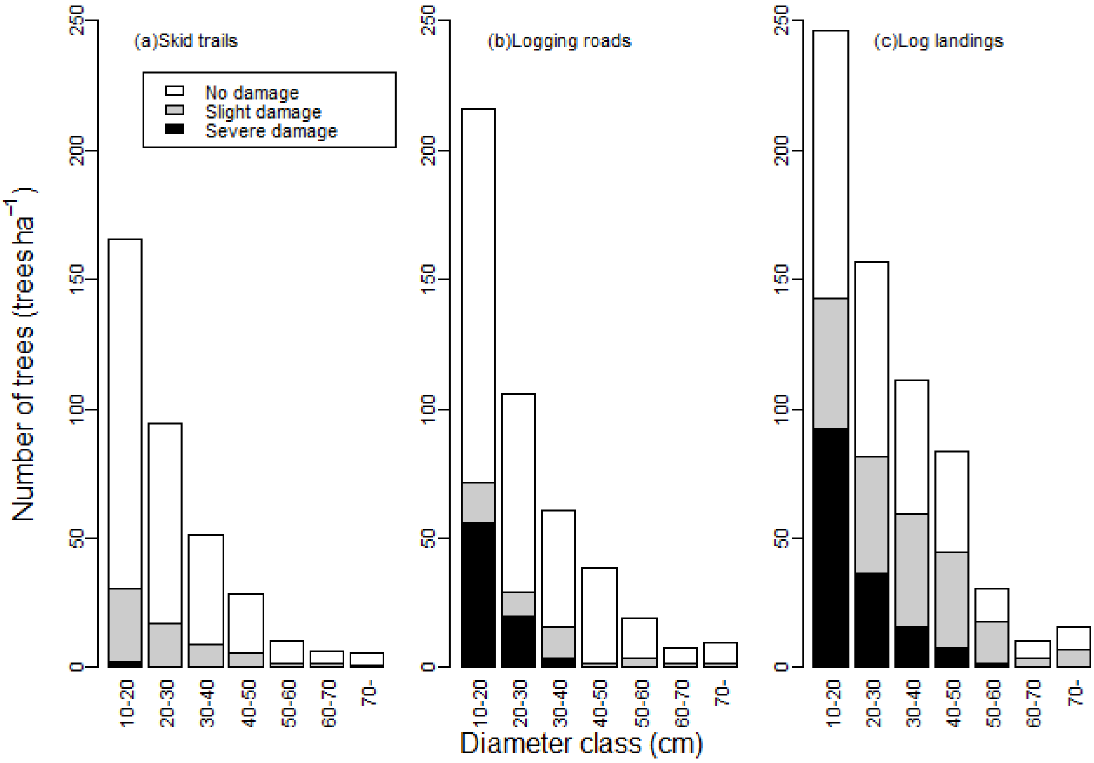

Figure 3-3 Number per ha of residual tree damage classes for each DBH class along each of operational areas

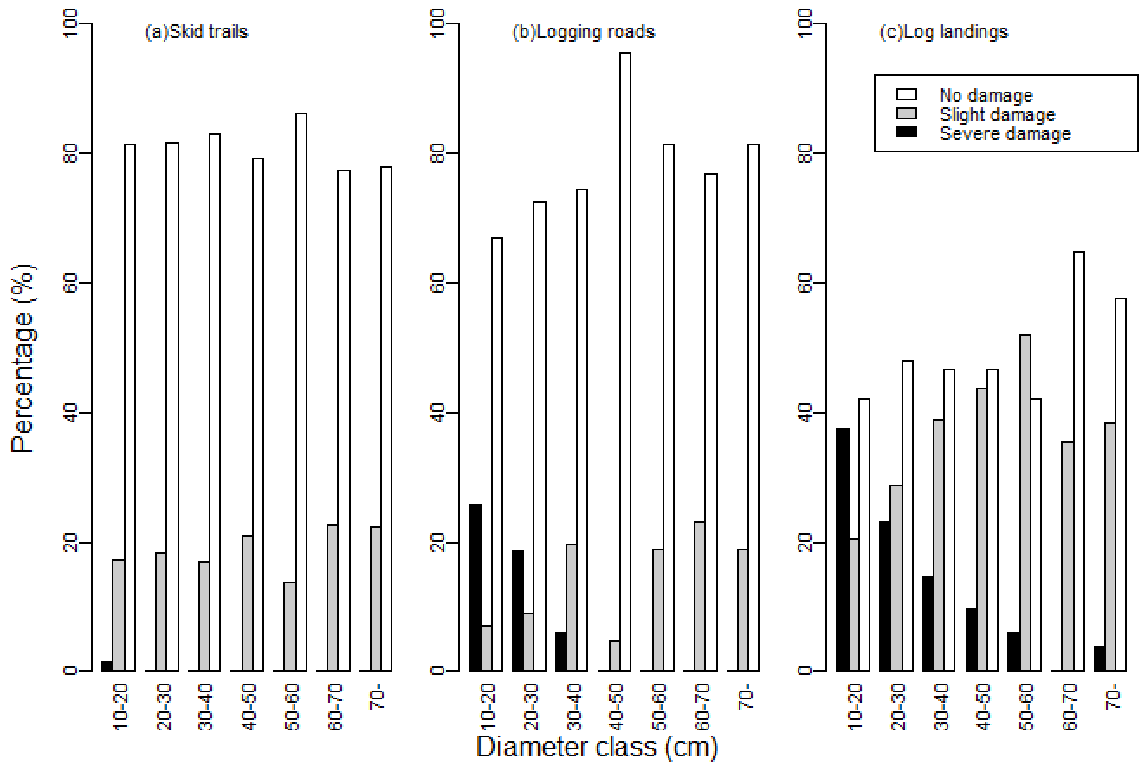

Figure 3-4 The results of multinomial models comparing each of slight and severe damage with no damage

3.3.2 Probability of damage to residual trees along each operational area

Analysis of the multinomial generalized linear mixed models showed that inclusion of the logarithm of DBH of residual tees as fixed effects was significant except for skid trails (chi-squared $P < 0.001$) as compared with a constant-only model (Table 3-3). DBH of residual trees affected the damage probabilities in different ways between severe and slight damage for logging roads and log landings (Figure 3-5, Table 3-3). The probability of severe damage largely decreased, approaching zero with increasing residual-tree DBH, while the probability of slightly damage increased (Figure 3-5). The probability of no damage was relatively constant for > 40-cm residual-tree DBH (Figure 3-5).

The model prediction shown in Figure 3-5 also confirms that severe damage of skid trails is almost zero regardless of residual trees' size, while slight damage is almost constant at the probability of 0.2. Such low-level damage from elephant skidding in Myanmar is quite different from damage found in machine skidding. For example, Sist et al., (1998) showed machine skidding induced twice trees killed (83 trees ha^{-1}) mainly from uprooting than trees injured (41 trees ha^{-1}) mainly at bark and wood. These results imply that it is difficult for the skidding machine to avoid falling down residual trees while elephants can move more easily in space between trees.

Table 3-3 The results of the multinomial models comparing each of slight and severe damage with no damage

Damage category	Variable	Estimate	SE	z-value	P
Skid trails					
Slight damage	Intercept	-1.665	0.388	-4.290	0.0000
	Log of DBH	0.046	0.123	0.375	0.7080
Severe damage	Intercept	3.357	2.737	1.226	0.2200
	Log of DBH	-2.919	1.034	NA	NA
Logging roads					
Slight damage	Intercept	-3.243	0.746	-4.345	0.0000
	Log of DBH	0.394	0.227	1.734	0.0828
Severe damage	Intercept	2.648	0.675	3.920	0.0001
	Log of DBH	-1.368	0.231	-5.918	0.0000
Log landings					
Slight damage	Intercept	-2.246	0.49	-4.583	0.0000
	Log of DBH	0.556	0.145	3.827	0.0001
Severe damage	Intercept	3.229	0.546	5.914	0.0000
	Log of DBH	-1.248	0.176	-7.075	0.0000

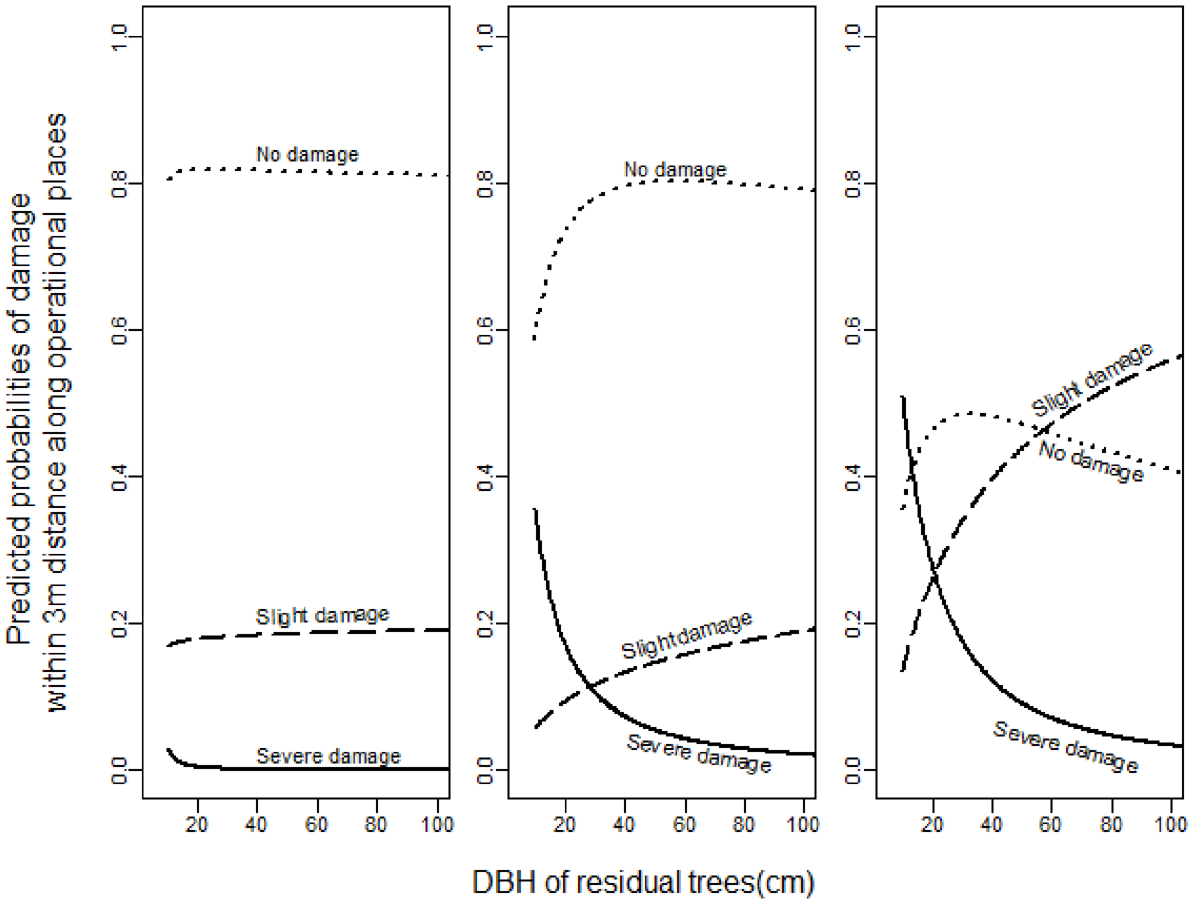

Figure 3-5 Effects of DBH of the residual trees on the predicted probability of a residual tree exhibiting severe, minor, or no damage along each operational area

3.3.3 Damage rate in relation to felling intensity per 1.0-ha

Our model prediction shows that residual tree damage rate (% ha^{-1}) increases when logging intensity increases except for logging roads (Figure 3-6). Among different operations, felling induces the most damage, followed by skidding, and damage along log landing and logging roads is relatively too small over different logging intensity (Figure 3-6). It is interesting that our prediction of felling damage in Myanmar shows similar levels found in the other studies in Indonesia (Sist et al., 1998 and 2003), Gabon (Medjibe et al., 2011) and Guyana (Van der Hout, 1999) (Figure 3-6). In contrast, skidding damage in Myanmar was the lowest level as compared to three case studies. It is common that skidding damage is similar to or more than felling damage (Sist et al., 1998), while our prediction indicated that skidding damage is less than half of felling damage regardless logging intensity (Figure 3-6). Such the lowest level of skidding damage was due to very little severe damage regardless of logging intensity while slight damage levels are similar between felling and skidding (Figure 3-7). A total cumulative damage level predicted in Myanmar is lower than global average estimated by Picard et al., 2012 consistently over different logging intensity (Figure 3-7), even though our liner prediction tends to overestimate the values at larger logging intensity because curvilinear relations are more likely found.

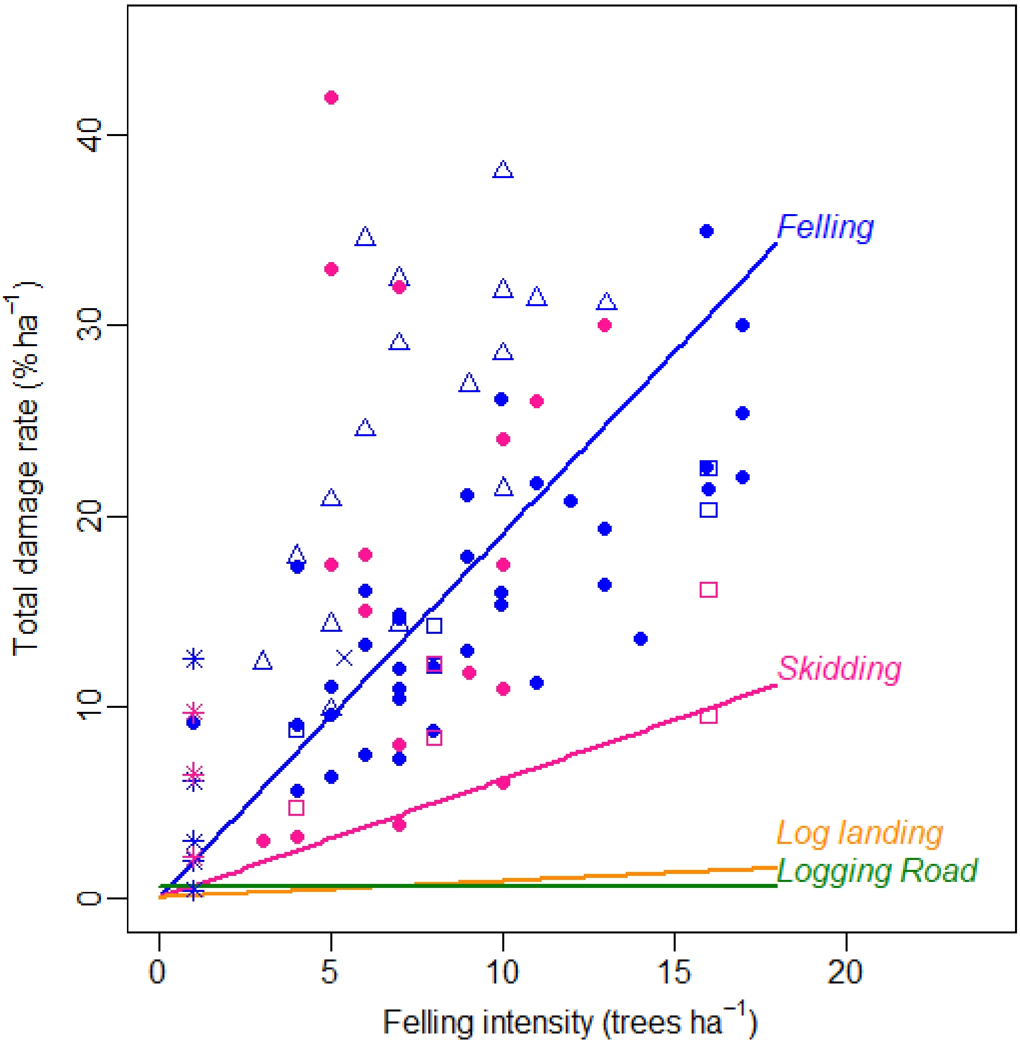

Figure 3-6 Relationships between logging intensity (trees ha-1) and total damage rate (%). The four lines were estimated from the equations (14), (15), (16) and (19) using data from Myanmar. As in Chheng et al., (2015), the symbols indicate data from the references by Sist et al., (1998) (●), Sist et al., (2003) (△), Webb (1997) (×), Van der Hout (1999) (□)and Medjibe et al. (2011) (✳). Blue and red symbols indicate damage from felling and skidding, respectively

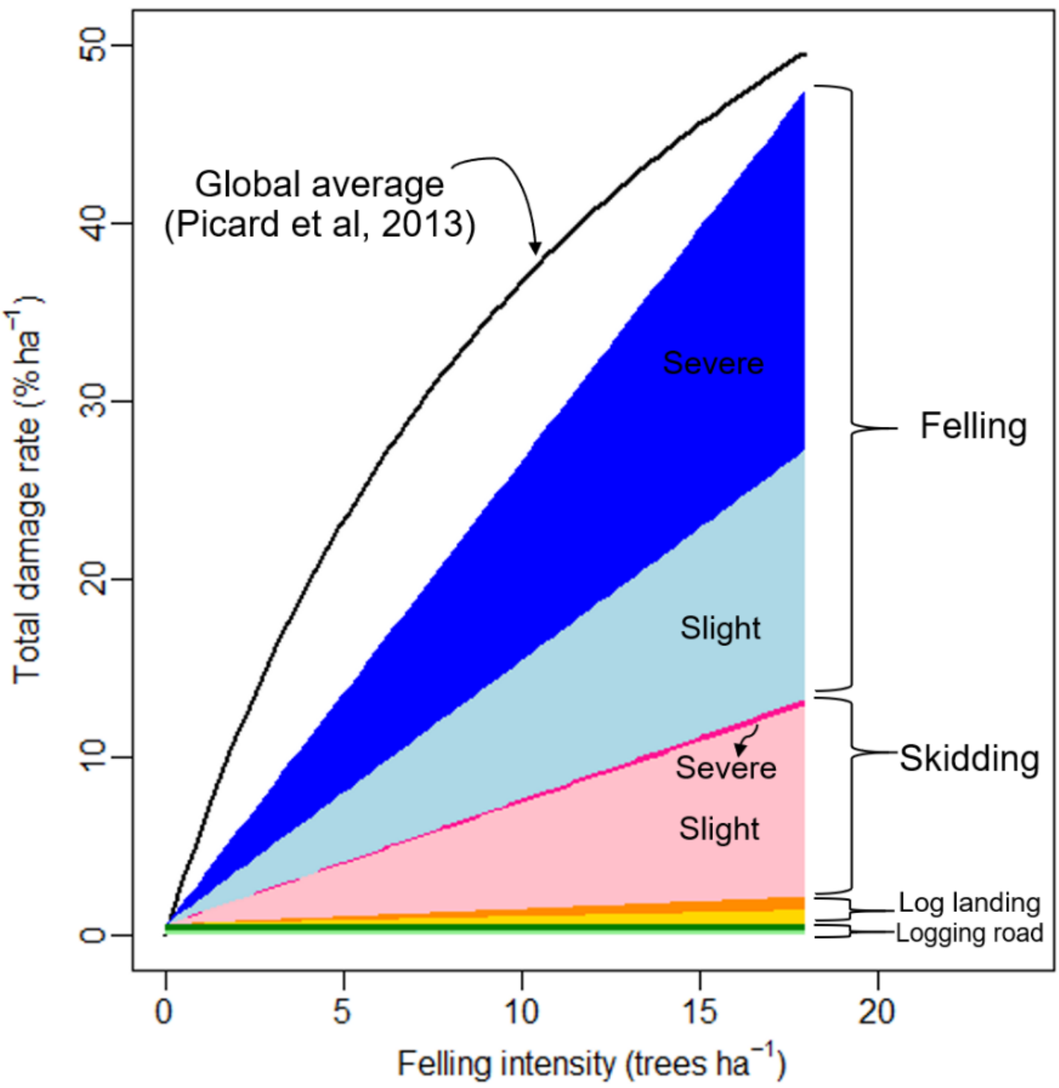

Figure 3-7 Relationships between logging intensity (trees ha-1) and cumulative rates of the severe or slight damage classes for felling, skidding, log landing and logging roads. Darker (lighter) colors for each operation indicate severe (slight) damage

3.4 Conclusion

I conclude that skidding using elephants contributes the lowest levels of residual tree damage as a whole with comparison to other countries' cases that used machine for skidding where the skidding damage is highest or second highest among the operations. The present results support our previous study on ground disturbance, encouraging to use a longer cable winch for skidding in other countries to minimize residual tree damage during skidding because there is a similarity between the elephant skidding and cable skidding in terms of the damage zone where only the movement of the logs and chains produce the damage.

CHAPTER IV

Movements of Semi-captive Elephants during Skidding Season in Myanmar

4.1 Introduction

Selective logging is a common logging practice, especially in tropical natural forests (Bicknell et al., 2014). Because only trees satisfying particular criteria are removed during selective logging, well-planned and carefully controlled selective logging has a small negative impact on biodiversity (Burivalova et al., 2015; Gibson et al., 2011). However, selective logging can result in forest degradation or intensive ground disturbance (Pereira et al., 2002) if conducted without careful planning (Pereira et al., 2002). There is thus a need for more studies of selective logging practices to aid the sustainable management of tropical forests.

Myanmar is a country in Southeast Asia with a long history of selective logging under the Myanmar Selection System (MSS). Selective logging under the MSS results in considerably lower ground disturbance compared with selective logging in other countries (Khai et al., 2020), which is mainly associated with the use of Asian elephants (*Elephus maximus*) for skidding (Khai et al., 2020). The elephants used for skidding are semi-captive, which means that they are partially free-ranging when off duty. Elephant care and management are critically important given that semi-captive elephants are essential for the MSS. An understanding of the behavior of semi-captive elephants is necessary for optimizing elephant management.

An understanding of the behavior of semi-captive elephants used in the MSS is also important for the conservation of Asian elephants. The Asian elephant is listed as an endangered species by the international union for conservation of nature red list of threatened speciesin (IUCN Red List) (Choudhury et al., 2008). Although the exact population size of the Asian elephant is not known, the estimated total population of the Asian elephant is approximately 63,000–67,000 (Menon and Tiwari, 2019). Captive and semi-captive Asian elephants account for approximately 15,000 (23%) of the total estimated population of Asian elephants. Because captive elephants in zoos only number ca. 1,000 and rarely breed (Sukumar, 2006), appropriate management of semi-captive Asian elephants is critically important for the conservation of Asian elephants. The number of semi-captive elephants used in the MSS is more than 3,000 (Ministry of Natural Resources and Environmental Conservation, 2018), and more than 1000 elephants are engaged in skidding operations. The rest are old and unfit, pregnant and young elephants not mature enough to perform skidding operation. All are managed and conserved under regular check, appetites, medical treatment and close care. Therefore, appropriate management of semi-captive elephants used in the MSS is important for the conservation of Asian elephants because such a large population represents 20% of the captive and semi-captive Asian elephants in the world.

Recently, an increasing number of studies have focused on the semi-captive elephants. However, the behavior of elephants when off duty has not yet been examined. Most studies of semi-captive elephants have focused on topics related to elephant populations, such as mortality rate (Mar et al., 2012), reproduction (Robinson et al., 2012), and population dynamics (Jackson et al., 2019). Other studies have focused on the personality of elephants (Seltmann et al., 2019, 2018) and their diet (Campos-Arceiz et al., 2008). Crawley et al., (2019) investigated the attitude and experience of elephant handlers and their relationships to recent political and economic changes in Myanmar. No studies to date have investigated the behavior of the semi-captive elephants used in the MSS.

Here, I studied the behavior of semi-captive elephants used in the MSS when they were being used for skidding and when off-duty. I tracked the movements of three semi-captive elephants using a global navigation satellite system (GNSS) and determined the moving speed and moving distance of the elephants. I expect that this quantitative information on their movements will facilitate the management and conservation of semi-captive elephants.

4.2 Context: Ordinary daily schedule of semi-captive elephants in the skidding season

The skidding season generally starts from the first of June to 15 of February while the weather is not hot and the skidding ground is easy to work due to seasonal rains. During the skidding season, elephant handlers stay at a camp with temporary housing near the skidding site. Selection of the skidding camp is selected where there is near to a stream. The camp is also where the semi-captive elephants spend much of their time when off duty.

Before skidding, the elephant handler locates the semi-captive elephants that were released the previous night and escorts them to the camp. The elephants are then washed in a stream and fed a light meal including tamarinds and salts. The health status of the elephants is also examined when they are being washed. After that, semi-captive elephants and the handlers leave the camp for skidding. After skidding, the semi-captive elephants and handlers return to the camp, the health status of the elephants is assessed, and elephants are fed a light meal. Generally, one elephant is fed 0.16 kg of tamarind and 0.08 kg of salt combined as a tamarind ball. This helps the elephants' health as an appetizer and as a digestive catalyst. This amount is applied to the skidding elephants during the skidding season but half of the amount is applied during normal period. Semi-captive elephants are generally released to forests to rest and forage. Sometimes, the elephants are not free to roam but instead tied to a place where food is ample near the camp depending on their health. This is a procedure that is occasionally employed when necessary. When elephants are at the camp, they are provided with food, bathed, and subjected to health assessments.

In this study, I tracked the movements of elephants (1) during skidding and (2) when semi-captive elephants were free to roam, which are hereafter referred to as work time and free time, respectively. The movements of elephants when the handlers were caring for them in the camp were not tracked because they generally stayed at the camp when under the care of their handlers.

4.3 Study Area

The study site was located in compartment 18 of Pyinde Reserved Forest in Katha and Kawlin, Myanmar (23°57′–58′N, 95°55′–57′E). The site is mountainous with an altitudinal range from 196 to 350 m above sea level. The forests are dominated by hardwood species such as teak (*Tectona grandis*), tauk-kyant (*Terminalia tomentosa*), and bamboo (*Thyrsostachys oliveri*). Monthly average temperature is ranging from 21°C to 31°C and monthly average rainfall is ranging from 4.8mm to 489.8mm. Some part of the surroundings is dominated by deciduous trees. The constitution of bamboo is around 40 of the plant community. During the measurement, a logging road is constructed in the logged compartment and the path is sometimes used for access.

4.4 Materials and Methods

4.4.1 GNSS Tracking and Time Records

Three semi-captive elephants were fitted with handheld GNSSs (GPSmap 62SJ, Garmin Ltd., Schaffhausen, Switzerland) by hitching a collar around their necks and were tracked from 11:15 on December 23th to 16:30 on December 27th in 2019 (Figure 4-1).

Figure 4-1 An example of semi-captive elephants with a GNSS

I focused on the behavior of semi-captive elephants during their free time and work time. Work time was defined as the period between the time when the elephants left the camp for skidding and the time when the elephants returned to the camp. Free time was defined as the period between the time when the elephants were released from the camp and the time when the elephants returned to the camp. The elephants were equipped with the handheld GNSS just before their work time and free time, and it was removed when they returned to the camp. The start and end time of the work time and free time for each elephant was also recorded. The GNSS data were acquired approximately every 30 s during the tracking period.

The elephants were 19–35 years old. Two elephants were male, and the other was female. Table 4-1 summarized the features of the elephants fitted with GNSSs. The GNSS fell off an elephant during free time one time. I found this GNSS in the field and could estimate the time when the GNSS fell off the elephant because the GNSS tracking data showed the time when the GNSS arrived at the point where it fell off. I thus removed data acquired after the GNSS fell off the elephant in our analysis.

Table 4-1 Summary of the features of elephants fitted with GNSSs

Elephant	Sex	Age (years)	MTE classification
1	Male	19	Full growth
2	Male	29	Full growth
3	Female	35	Full growth

4.4.2 Data Analysis

Before analyzing the data, we categorized the GNSS data into two classes: free time and work time. We then removed outlier points based on the moving speed and turning angle following previous studies of animal movement using GNSS data (Bjørneraas et al., 2010). Points exceeding the pre-defined moving speed were defined as outliers. Points were also classified as outliers when the turning angle was smaller than the pre-defined threshold. In this study, we defined the pre-defined moving speed threshold and the turning angle threshold as 5.18 km/hour and 1.72 degrees, respectively. Outliers corresponded to the 1 percentile of all data points. If a given point (outlier) was removed, the moving speed and turning angle were updated using the new data set without the outlier. Because the updated moving speed and turning angle may still exceed the pre-defined threshold, we recursively removed the outliers until the updated moving speed and turning angle satisfied the criteria.

After filtering the GNSS data, we calculated the distance from the camp and the moving distance. The distance from the camp was defined as the horizontal distance between the center of the camp and each GNSS data point. The center location of the camp was recorded using a handheld GNSS (GPS map 62SJ). The distances were summarized for every elephant by discriminating free time and work time (i.e., the time for skidding).

The moving distance was also calculated horizontally. Based on the GNSS data classified into work time and free time, we calculated the total moving distance and hourly moving distance of each elephant by dividing the total moving distance by the free time and work time.

The analysis was conducted in R ver. 4.0.3 (R Core Team, 2021).

4.5 Results and Discussion

All three elephants spent approximately the same amount of time skidding (ca. 13% of the study period), but the amount of free time varied (ranging from 63% to 80%) (Figure

4-2). As the elephant are working a unit, the time duration spent is same for all elephants in the group unit. In general, the movements of the elephants are individually and slightly different based on sex, age, food choice and preferred territory and sometimes due to health condition. The reason for the variation in the amount of free time is that some elephants (elephant 2 and 3 in Table 4-1) were tied down for long periods because of their health status needs close examination, as described in section 2.

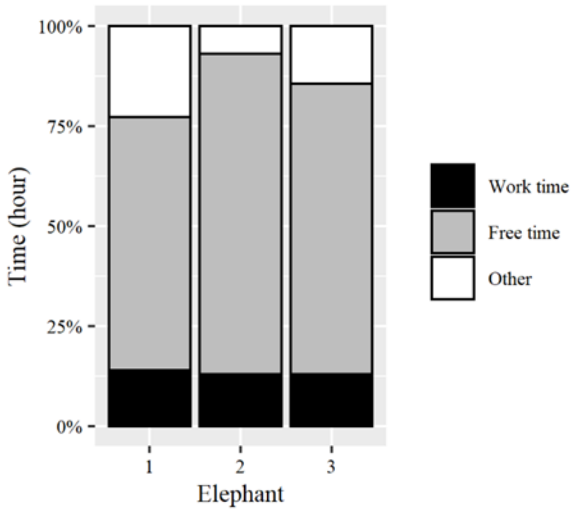

Figure 4-2 Free and work time ratio of each elephant.

The tracks varied among elephants during free time but were concentrated around the camp, which was in contrast to their tracks during work time (Figure 4-3). The mean distances from the camp for each elephant were between 0.172 and 0.364 km for free time (Figure 4-4) and significantly varied among elephants ($P < 0.05$) (Games-Howell test). The maximum distance that elephants moved from the camp was 0.875 km. The mean and maximum distances suggested that the elephants were located near the camp where elephant handlers could find them. The tracks of the three elephants during work time were similar (Figure 4-3). The mean distances from the camp for each were between 1.365 and 1.396 km (Figure 4-4) and did not significantly differ among elephants ($P > 0.05$) (Games-Howell test). This is not surprising because all three elephants went to the same logging sites and worked as a group during the study period.

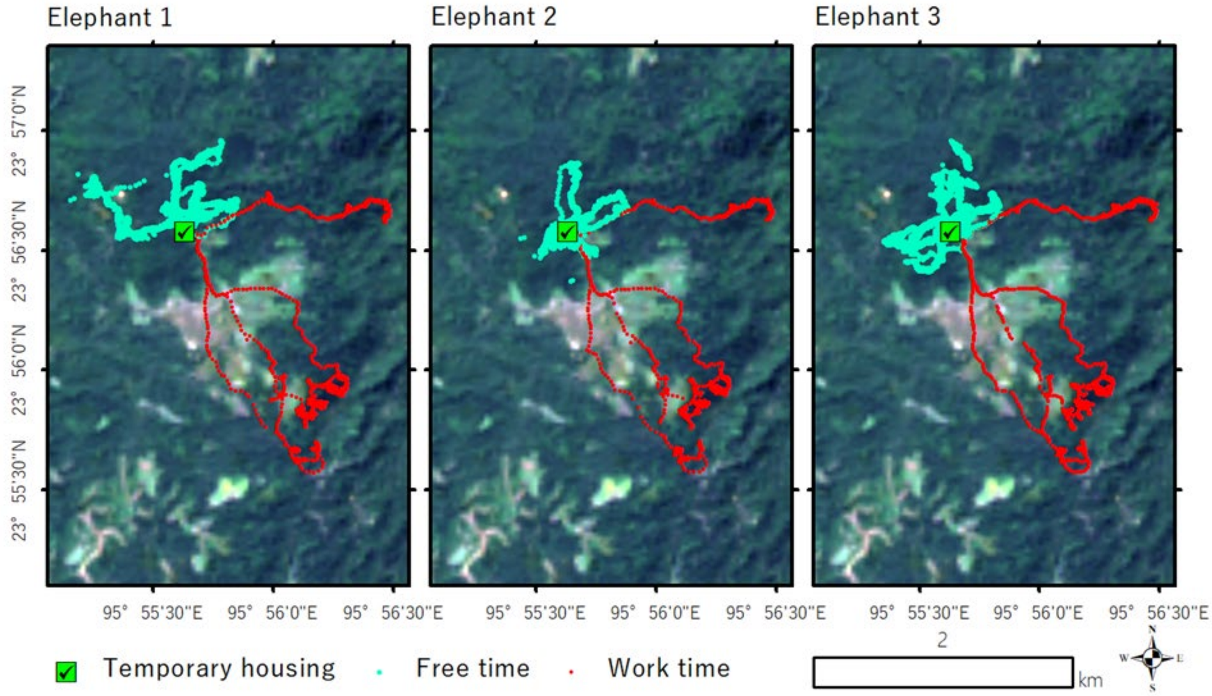

Figure 4-3 Movement trajectories of elephants and the location of the camp of elephant handlers. The background image is the true-color image derived from Landsat 8 (acquired November 18, 2019

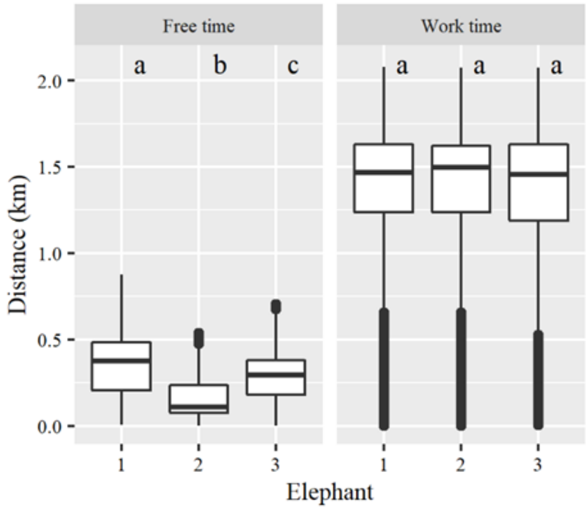

Figure 4-4 Distance from the camp of elephant handlers

The total moving distances of elephants during free time were more than twice as long as the total moving distances during work time (Figure 4-5). This was because the duration of free time was much longer than the duration of work time (Figure 4-2). The hourly moving distance was between 0.622 and 0.655 km and between 1.522 and 1.629 km for free time and work time, respectively (Figure 4-5). According to Leighty et al. (2009), the hourly distance traveled by wild Asian elephants ranged from 0.010 to 1.500 km. The hourly distance traveled by semi-captive elephants in both free time and work time was similar to that of wild Asian elephants, but the hourly distance in work time was close to the upper limit of the hourly distance traveled by wild Asian elephants.

Semi-captive elephants spent their free time within 0.875 km of the camp. Because the semi-captive elephants forage (especially bamboo) and rest during free time, sufficient supplies of food near the camp are needed. Therefore, the conservation of forest in areas used for camp is important for the MSS as well as the conservation of Asian elephants.

4.6 Conclusion

The semi-captive elephants mainly spent their time within 0.875 km of the camp of the elephant handler, but there was some variation among individuals when semi-captive elephants were off duty. During work time, the elephants needed to go more than 1 km away from the camp. No significant differences in the movements between elephants were observed during work time because the elephants worked as a group. The hourly moving distance of the semi-captive elephants during free time and work time in this study was similar to that of wild elephants. Additional studies are needed to explore the movement behavior of semi-captive elephants under other seasonal schedules, in resting camps, in tourism camps, and in other skidding sites.

CHAPTER V
General Conclusion and Recommendation

The tropical forests play an important role for biodiversity and also for the timber production. Timber harvesting in tropical forests can support production and services and economic benefits. However, the logging practice applied for the tropical timber production known as the selective logging has also been considered as one of the proximate causes of deforestation and forest degradation. There are two main selective logging practices: the conventional logging (CON) and the reduced-impact logging (RIL). Controversially, the latter is generally assumed to produce lower impact because the unsupervised logging operations by the former generate higher soil disturbance and damage in residual stand.

In Myanmar, a selective logging system called the Myanmar Selection System (MSS) has been practiced over decades. Different from the use of machines in skidding operations in other countries, elephants are used in the skidding operation in MSS. The elephants used in skidding are semi-captive Asian Elephant (*Elephas Maximus*). Semi-captive is a management system in which the elephant can range and forage in their free time and not fully-captive as the zoo elephants. The use of elephant in skidding is considered to have potentials to reduce the impacts compared with the machines. To evaluate the impacts of elephant skidding and the other two logging operations (the construction of logging roads and log landing), this study was conducted in two area of Myanmar. The Bago (South) extraction agency is located in the southern part of Myanmar and the Katha (East) extraction agency is located in the northern part. This study was initiated in 2014 and the field surveys were conducted up to 2018. Additionally, the moving behavior of the skidding elephants around the skidding camp was also examined because the conservation of the semi-captive elephants is becoming very important while the wild elephants become endangered.

The elephant skidding show lower impact than the mechanical skidding of the other countries in terms of soil disturbance while the other two operations (the construction of logging roads and log landing) show no large difference. The narrower width of the elephant moving track may be a main reason and the soil disturbance is a result of the log movement by the elephants. The evaluation of skidding impacts to the residual stands also supported the main research hypothesis that the use of elephants may produce lower impacts on residual trees than the machines. This thesis does not intend to suggest the other countries to use elephants for skidding, but my results encourage the use of long winch cables in machine skidding of the other countries to minimize the movement of machines and thus reduce the disturbance to residual stands substantially to levels closer to those for elephant skidding.

The use of elephants in skidding evaluated in this study show lower impacts than the machines in other countries. On the other hand, the semi-captive elephants have also potentials for the conservation of Asian elephants while the wild elephants become endangered. Three elephants from a skidding site under the MSS were evaluated to understand the movement behavior so as to compare with the wild elephants. The tracking of the elephants in Katha area of Myanmar was conducted in December of 2019 for five days. The evaluation was focused on the working time and free time of the elephants because the selected elephants were involved in skidding operations. The movement of the semi-captive elephant is not so much different from those of the wild elephants. Moreover, there is a key finding that the elephants spend most of their time around the skidding basecamp while they are freely ranging for the food and are freely wondering for their rest. It points out that the surrounding area of the elephant ranging zone is important to be conserved in order to maintain the elephant population stable. The tracking of moving behavior of semi-captive elephants in this study only focused on elephants in a skidding site.

There are some limitations in this thesis, which should be exceeded in the future studies. The impacts of selective logging result not only from the logging operations that were evaluated in this thesis. The impacts, at least, from tree felling should be integrated in the impact evaluation process. This thesis evaluated the impacts in terms of tree number and/or stem volumes of trees that suffered from immediate physical impacts. Thus, the carbon-based studies should be combined with such physical impacts by logging operations. Evaluating the moving behavior of semi-captive elephants was only for three elephant, calling for additional samples with different age, sex and camp categories such as tourism camps and resting camps. The impacts of selective logging resulted not only from the logging operations that were evaluated in this study. The impact by tree felling should be integrated in the impacts evaluation process. Moreover, the carbon-based studies should be combined with such kind of immediate physical impacts by logging operations. Among more than 3,000 of the total semi-captive elephants, one thirds are engaged in skidding operations, while the rest two thirds are in the other classifications of semi-captive elephants such as the training elephants younger than 18 years, tourism elephants and so on. Reducing the logging activities in recent years in Myanmar leaded to higher populations of semi-captive elephants other than the skidding elephants. Similar studies of evaluating moving behavior of such other semi-captive elephants are strongly recommended to maintain the current population which stands almost stable in recent years.

References

Asner, G.P., Keller, M., Silva, J.N.M., 2004. Spatial and temporal dynamics of forest canopy gaps following selective logging in the eastern Amazon. Glob. Chang. Biol. 10, 765–783. https://doi.org/10.1111/j.1529-8817.2003.00756.x

Berry, N.J., Phillips, O.L., Ong, R.C., Hamer, K.C., 2008. Impacts of selective logging on tree diversity across a rainforest landscape: The importance of spatial scale. Landsc. Ecol. 23, 915–929. https://doi.org/10.1007/s10980-008-9248-1

Bertault, J., Sist, P., 1997. An experimental comparison of different harvesting intensities with reduce-impact and conventional logging in East Kalimantan, Indonesia. For. Ecol. Manage. 94, 209–218.

Bertault, J.G., Sist, P., 1997. An experimental comparison of different harvesting intensities with reduced-impact and conventional logging in East Kalimantan, Indonesia. For. Ecol. Manage. 94, 209–218. https://doi.org/10.1016/S0378-1127(96)03974-6

Bicknell, J.E., Struebig, M.J., Edwards, D.P., Davies, Z.G., 2014. Improved timber harvest techniques maintain biodiversity in tropical forests. Curr. Biol. 24, R1119–R1120. https://doi.org/10.1016/j.cub.2014.10.067

Bjørneraas, K., Van Moorter, B., Rolandsen, C.M., Herfindal, I., 2010. Screening global positioning system location data for errors using animal movement characteristics. J. Wildl. Manage. 74, 1361–1366. https://doi.org/10.2193/2009-405

Blaser, J., Sarre, A., Poore, D., Johnson, S., 2011. Status of Tropical Forest Management 2011, ITTO Technical Series. https://doi.org/10.1017/S0032247400051135

Brunner, J., Talbott, K., Elkin, C., 1988. Logging Bruma's Frontier Forests: Resources and the Regime.

Burivalova, Z., Lee, T.M., Giam, X., Sekercioglu, Ç.H., Wilcove, D.S., Koh, L.P., 2015. Avian responses to selective logging shaped by species traits and logging practices. Proc. R. Soc. B Biol. Sci. 282. https://doi.org/10.1098/rspb.2015.0164

Campos-Arceiz, A., Lin, T.Z., Htun, W., Takatsuki, S., Leimgruber, P., 2008. Working with mahouts to explore the diet of work elephants in Myanmar (Burma). Ecol. Res. 23, 1057–1064. https://doi.org/10.1007/s11284-008-0466-4

Chheng, K., Mizoue, N., Khorn, S., Kao, D., Sasaki, N., 2015. Tree-based approach to evaluate size dependence of residual tree damage caused by selective logging: Case study in tropical semi-evergreen forests of Cambodia. For. Ecol. Manage. 356, 285–292. https://doi.org/10.1016/j.foreco.2015.06.031

Choudhury, A., Lahiri Choudhury, D.K., Desai, A., Duckworth, J.W., Easa, P.S., Johnsingh, A.J.T., Fernando, P., Hedges, S., Gunawardena, M., Kurt, F., Karanth, U., Lister, A., Menon, V., Riddle, H., Rübel, A., Wikramanayake, E., 2008. Elephas maximus. The IUCN Red List of Threatened Species 2008: e.T7140A12828813. [WWW Document]. https://doi.org/10.2305/IUCN.UK.2008.RLTS.T7140A12828813.en

Crawley, J.A.H., Lahdenperä, M., Seltmann, M.W., Htut, W., Aung, H.H., Nyein, K., Lummaa, V., 2019. Investigating changes within the handling system of the largest semi-captive population of Asian elephants. PLoS One 14, 1–14. https://doi.org/10.1371/journal.pone.0209701

Dah, S.E., 2004. Teak and forest management in Myanmar. ITTO Trop. For. Updat. 14, 12–13.

Darrigo, M.R., Venticinque, E.M., Santos, F.A.M. dos, 2016. Effects of reduced impact logging on the forest regeneration in the central Amazonia. For. Ecol. Manage. 360, 52–59. https://doi.org/10.1016/j.foreco.2015.10.012

Edwards, D.P., Woodcodk, P., Edwards, F.A., Larsen, T.H., Hsu, W.W., Benedick, S., Wilcove, D.S., 2012. Reduced-impact logging and biodiversity conservation: A case study from Borneo. Ecol. Appl. 22, 561–571.

Ellis, P.W., Gopalakrishna, T., Goodman, R.C., Putz, F.E., Roopsind, A., Umunay, P.M., Zalman, J., Ellis, E.A., Mo, K., Gregoire, T.G., Griscom, B.W., 2019. Reduced-impact logging for climate change mitigation (RIL-C) can halve selective logging emissions from tropical forests. For. Ecol. Manage. 438, 255–266. https://doi.org/10.1016/j.foreco.2019.02.004

FAO, 2004. Reduced Impact Logging. For. Harvest. Eng. Work. Pap. No.1 8.

Feldpausch, T.R., Jirka, S., Passos, C.A.M., Jasper, F., Riha, S.J., 2005. When big trees fall: Damage and carbon export by reduced impact logging in southern Amazonia. For. Ecol. Manage. 219, 199–215. https://doi.org/10.1016/j.foreco.2005.09.003

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E., Sodhi, N.S., 2011. Primary forests are irreplaceable for sustaining tropical biodiversity. Nature 478, 378–81. https://doi.org/10.1038/nature10425

Goodman, R.C., Harman Aramburu, M., Gopalakrishna, T., Putz, F.E., Gutiérrez, N., Mena Alvarez, J.L., Aguilar-Amuchastegui, N., Ellis, P.W., 2019. Carbon emissions and potential emissions reductions from low-intensity selective logging in southwestern Amazonia. For. Ecol. Manage. 439, 18–27. https://doi.org/10.1016/j.foreco.2019.02.037

Griscom, B., Ellis, P., Putz, F.E., 2014. Carbon emissions performance of commercial logging in East Kalimantan, Indonesia. Glob. Chang. Biol. 20, 923–937. https://doi.org/10.1111/gcb.12386

Griscom, B.W., Ellis, P.W., Burivalova, Z., Halperin, J., Marthinus, D., Runting, R.K., Ruslandi, Shoch, D., Putz, F.E., 2019. Reduced-impact logging in Borneo to minimize carbon emissions and impacts on sensitive habitats while maintaining timber yields. For. Ecol. Manage. 438, 176–185. https://doi.org/10.1016/j.foreco.2019.02.025

Gullison, R.E., Hardner, J.J., 1993. The effects of road design and harvest intensity on forest damage caused by selective logging: empirical results and a simulation model from the Bosque Chimanes, Bolivia. For. Ecol. Manage. 59, 1–14. https://doi.org/10.1016/0378-

1127(93)90067-W

Jackson, J., Childs, D.Z., Mar, K.U., Htut, W., Lummaa, V., 2019. Long-term trends in wild-capture and population dynamics point to an uncertain future for captive elephants. Proceedings. Biol. Sci. 286, 20182810. https://doi.org/10.1098/rspb.2018.2810

Johns, J.S., Barreto, P., Uhl, C., 1996. Logging damage during planned and unplanned logging operations in the eastern Amazon. For. Ecol. Manage. 89, 59–77. https://doi.org/10.1016/S0378-1127(96)03869-8

Keenan, R.J., Reams, G.A., Achard, F., de Freitas, J. V., Grainger, A., Lindquist, E., 2015. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015. For. Ecol. Manage. 352, 9–20. https://doi.org/10.1016/j.foreco.2015.06.014

Khai, T.C., Mizoue, N., Kajisa, T., Ota, T., Yoshida, S., 2017. Using a tree-based approach to evaluate logging damage in a tropical mixed deciduous forest of Myanmar: Comparison with cases in Cambodia. J. For. Res. 22, 185–190. https://doi.org/10.1080/13416979.2017.1302545

Khai, T.C., Mizoue, N., Kajisa, T., Ota, T., Yoshida, S., 2016. Effects of Directional Felling, Elephant Skidding and Road Construction on Damage to Residual Trees and Soil in Myanmar Selection System. Int. For. Rev. 18, 296–305. https://doi.org/10.1505/146554816819501718

Khai, Tual Cin, Mizoue, N., Ota, T., 2020. Harvesting intensity and disturbance to residual trees and ground under Myanmar selection system; comparison of four sites. Glob. Ecol. Conserv. 24. https://doi.org/10.1016/j.gecco.2020.e01214

Khai, T.C., Mizoue, N., Ota, T., 2020. Harvesting intensity and disturbance to residual trees and ground under Myanmar selection system; comparison of four sites. Glob. Ecol. Conserv. 24, e01214. https://doi.org/10.1016/j.gecco.2020.e01214

Kleinschroth, F., Healey, J.R., Sist, P., Mortier, F., Gourlet-Fleury, S., 2016. How persistent are the impacts of logging roads on Central African forest vegetation? J. Appl. Ecol. 53, 1127–1137. https://doi.org/10.1111/1365-2664.12661

Leighty, K.A., Soltis, J., Wesolek, C.M., Savage, A., Mellen, J., Lehnhardt, J., 2009. GPS determination of walking rates in captive African elephants (Loxodonta africana). Zoo Biol. 28, 16–28. https://doi.org/10.1002/zoo.20199

Mar, K.U., Lahdenperä, M., Lummaa, V., 2012. Causes and correlates of calf mortality in captive asian elephants (elephas maximus). PLoS One 7, 1–10. https://doi.org/10.1371/journal.pone.0032335

Medjibe, V.P., Putz, F.E., Romero, C., 2013. Certified and uncertified logging concessions compared in Gabon: Changes in stand structure, tree species, and biomass. Environ. Manage. 51, 524–540. https://doi.org/10.1007/s00267-012-0006-4

Medjibe, V.P., Putz, F.E., Starkey, M.P., Ndouna, A.A., Memiaghe, H.R., 2011. Impacts of selective logging on above-ground forest biomass in the Monts de Cristal in Gabon. For.

Ecol. Manage. 262, 1799–1806. https://doi.org/10.1016/j.foreco.2011.07.014

Menon, V., Tiwari, S.K.R., 2019. Population status of Asian elephants Elephas maximus and key threats. Int. Zoo Yearb. 53, 17–30. https://doi.org/https://doi.org/10.1111/izy.12247

Miller, S.D., Goulden, M.L., Hutyra, L.R., Keller, M., Saleska, S.R., Wofsy, S.C., Figueira, A.M.S., da Rocha, H.R., de Camargo, P.B., 2011. Reduced impact logging minimally alters tropical rainforest carbon and energy exchange. Proc. Natl. Acad. Sci. 108, 19431–19435. https://doi.org/10.1073/pnas.1105068108

Ministry of Natural Resources and Environmental Conservation, 2018. Myanmar elephant conservation action plan (MECAP): 2018-2027.

Minn, S.T., Mizoue, N., Ota, T., 2022. Evaluating ground disturbance at elephant skid trails, logging roads and log landings under the Myanmar selection system. J. For. Res. 00, 1–10. https://doi.org/10.1080/13416979.2022.2067618

Mon, M.S., Kajisa, T., Mizoue, N., Yoshida, S., 2010. Monitoring Deforestation and Forest Degradation in the Bago Mountain Area, Myanmar using FCD Mapper. Japan Soc. For. Plan. 15, 63–72.

Mon, M.S., Mizoue, N., Htun, N.Z., Kajisa, T., Yoshida, S., 2012. Factors affecting deforestation and forest degradation in selectively logged production forest: A case study in Myanmar. For. Ecol. Manage. 267, 190–198. https://doi.org/10.1016/j.foreco.2011.11.036

Montagnini, F., Jordan, C.F., 2005. Tropical Forest Ecology, Tropical Forestry. Springer-Verlag, Berlin/Heidelberg. https://doi.org/10.1007/b138811

Pereira Jr., R., Zweede, J., Asner, G.P., Keller, M., 2002. Forest canopy damage and recovery in reduced impact and conventional selective logging Eastern Pará, Brazil. For. Ecol. Manage. 168, 77–89.

Pereira, R., Zweede, J., Asner, G.P., Keller, M., 2002. Forest canopy damage and recovery in reduced-impact and conventional selective logging in eastern Para, Brazil. For. Ecol. Manage. 168, 77–89.

Picchio, R., Magagnotti, N., Sirna, A., Spinelli, R., 2012. Improved winching technique to reduce logging damage. Ecol. Eng. 47, 83–86. https://doi.org/10.1016/j.ecoleng.2012.06.037

Pinard, M.A., Barker, M.G., Tay, J., 2000. Soil disturbance and post-logging forest recovery on bulldozer paths in Sabah, Malaysia. For. Ecol. Manage. 130, 213–225. https://doi.org/10.1016/S0378-1127(99)00192-9

Pinard, M.A., Putz, F.E., 1996. Retaining Forest Biomass by Reducing Logging Damage.pdf.

Poudyal, H., Maraseni, T., Cockfield, G., 2018. Evolutionary dynamics of selective logging in the tropics: A systematic review of impact studies and their effectiveness in sustainable forest management. For. Ecol. Manage. 430, 166–175. https://doi.org/10.1016/j.foreco.2018.08.006

Putz, F.E., Zuidema, P.A., Synnott, T., Peña-Claros, M., Pinard, M.A., Sheil, D., Vanclay, J.K., Sist, P., Gourlet-Fleury, S., Griscom, B., Palmer, J., Zagt, R., 2012. Sustaining conservation values in selectively logged tropical forests: The attained and the attainable. Conserv. Lett. 5, 296–303. https://doi.org/10.1111/j.1755-263X.2012.00242.x

R Core Team, 2021. R: A Language and Environment for Statistical Computing [WWW Document].

Robinson, M.R., Mar, K.U., Lummaa, V., 2012. Senescence and age-specific trade-offs between reproduction and survival in female Asian elephants. Ecol. Lett. 15, 260–266. https://doi.org/10.1111/j.1461-0248.2011.01735.x

Runkle, J.R., 1992. Guidelines and Sample Protocol for Samping forest Gaps. Dep. Agric. For. Serv. 44.

Runting, R.K., Ruslandi, Griscom, B.W., Struebig, M.J., Satar, M., Meijaard, E., Burivalova, Z., Cheyne, S.M., Deere, N.J., Game, E.T., Putz, F.E., Wells, J.A., Wilting, A., Ancrenaz, M., Ellis, P., Khan, F.A.A., Leavitt, S.M., Marshall, A.J., Possingham, H.P., Watson, J.E.M., Venter, O., 2019. Larger gains from improved management over sparing–sharing for tropical forests. Nat. Sustain. https://doi.org/10.1038/s41893-018-0203-0

Ruslim, Y., Sihombing, R., Liah, Y., 2016. Stand damage due to mono-cable winch and bulldozer yarding in a selectively logged tropical forest. Biodiversitas, J. Biol. Divers. 17, 222–228. https://doi.org/10.13057/biodiv/d170132

Seltmann, M.W., Helle, S., Adams, M.J., Mar, K.U., Lahdenperä, M., 2018. Evaluating the personality structure of semi-captive asian elephants living in their natural habitat. R. Soc. Open Sci. 5. https://doi.org/10.1098/rsos.172026

Seltmann, M.W., Helle, S., Htut, W., Lahdenperä, M., 2019. Males have more aggressive and less sociable personalities than females in semi-captive Asian elephants. Sci. Rep. 9, 1–7. https://doi.org/10.1038/s41598-019-39915-7

Sessions, J., 2007. Forest Road Operations in the Tropics, Forest Roads in the Tropics. https://doi.org/10.1007/978-3-540-46393-1

Shenkin, A., Bolker, B., Peña-Claros, M., Licona, J.C., Putz, F.E., 2015a. Fates of trees damaged by logging in Amazonian Bolivia. For. Ecol. Manage. 357, 50–59. https://doi.org/10.1016/j.foreco.2015.08.009

Shenkin, A., Bolker, B., Peña-Claros, M., Licona, J.C., Putz, F.E., 2015b. Fates of trees damaged by logging in Amazonian Bolivia. For. Ecol. Manage. 357, 50–59. https://doi.org/10.1016/j.foreco.2015.08.009

Shimizu, K., Ahmed, O.S., Ponce-Hernandez, R., Ota, T., Win, Z.C., Mizoue, N., Yoshida, S., 2017a. Attribution of disturbance agents to forest change using a Landsat time series in tropical seasonal forests in the Bago Mountains, Myanmar. Forests 8, 1–16. https://doi.org/10.3390/f8060218

Shimizu, K., Ponce-hernandez, R., Ahmed, O.S., Ota, T., Win, Z.C., Mizoue, N., 2017b.

Using Landsat time series imagery to detect forest disturbance in selectively logged tropical forests in Myanmar. Can. J. For. Res. 47, 289–296. https://doi.org/https://doi.org/10.1139/cjfr-2016-0244

Sist, P., Nolan, T., Bertault, J.-G., Dykstra, D., 1998. Harvesting intensity versus sustainability in Indonesia. For. Ecol. Manage. 108, 251–260.

Sist, P., Sheil, D., Kartawinata, K., Priyadi, H., 2003. Reduced-impact logging in Indonesian Borneo: Some results confirming the need for new silvicultural prescriptions. For. Ecol. Manage. 179, 415–427. https://doi.org/10.1016/S0378-1127(02)00533-9

Sukumar, R., 2006. A brief review of the status, distribution and biology of wild Asian elephants Elephas maximus. Int. Zoo Yearb. 40, 1–8. https://doi.org/10.1111/j.1748-1090.2006.00001.x

Tavankar, F., Majnounian, B., Bonyad, A.E., 2013. Felling and skidding damage to residual trees following selection cutting in Caspian forests of Iran. J. For. Sci. 59, 196–203. https://doi.org/10.17221/53/2012-JFS

Umunay, P.M., Gregoire, T.G., Gopalakrishna, T., Ellis, P.W., Putz, F.E., 2019. Selective logging emissions and potential emission reductions from reduced-impact logging in the Congo Basin. For. Ecol. Manage. 437, 360–371. https://doi.org/10.1016/j.foreco.2019.01.049

Wadsworth, F.H., 1997. Forest production for tropical America. Agric. Handb. 710, 634.

Webb, E.L., 1997. Canopy removal and residual stand damage during controlled selective logging in lowland swamp forest of northeast Costa Rica. For. Ecol. Manage. 95, 117–129. https://doi.org/10.1016/S0378-1127(97)00020-0

Wilson, E.., 1993. The Diversity of Life, Penguin.

Win, R.N., Suzuk, R., Takeda, S., 2012a. Effects of Selective Logging on the Regeneration of two Commercial Species in the Kabaung Reserved Forest, Bago Mountains, Myanmar. J. Trop. For. Sci. Ne Win R al 24, 312–321.

Win, R.N., Suzuki, R., Takeda, S., 2012b. Remote sensing analysis of forest damage by selection logging in the Kabaung Reserved Forest, Bago Mountains, Myanmar. J. For. Res. 17, 121–128. https://doi.org/10.1007/s10310-011-0276-3

Win, Z.C., Mizoue, N., Ota, T., Kajisa, T., Yoshida, S., Oo, T.N., Ma, H., 2018a. Evaluating the Condition of Selectively Logged Production Forests in Myanmar: An Analysis Using Large-scale Forest Inventory Data for Yedashe Township. J. For. Plan. 23, 1–8. https://doi.org/10.20659/jfp.23.1_1

Win, Z.C., Mizoue, N., Ota, T., Wang, G., Innes, J.L., Kajisa, T., Yoshida, S., 2018b. Spatial and temporal patterns of illegal logging in selectively logged production forest: a case study in Yedashe, Myanmar. J. For. Plan. 23, 15–25. https://doi.org/10.20659/jfp.23.2_15

Zalman, J., Ellis, P.W., Crabbe, S., Roopsind, A., 2019. Opportunities for carbon emissions reduction from selective logging in Suriname. For. Ecol. Manage. 439, 9–17.

https://doi.org/10.1016/j.foreco.2019.02.026