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The Use of Landsat Imagery and Spatial Analysis to Detect Forest Cover Change and Degradation, and Determine Forest Management Suitability Indices in the Bago Mountain Region of Myanmar

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THE USE OF LANDSAT IMAGERY AND SPATIAL ANALYSIS TO DETECT FOREST COVER CHANGE AND DEGRADATION, AND DETERMINE FOREST MANAGEMENT SUITABILITY INDICES IN THE BAGO MOUNTAIN REGION OF MYANMAR

by

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LIST OF ABBREVIATIONS

AAC – Annual Allowable Cut

ANNs – Artificial Neutral Networks

CNES – Centre National d'Etudes Spatiales

CFI – Community Forestry Instructions

DBH – Diameter at Breast Height

DEM – Digital Elevation Model

DUMD – Dry Upper Mixed Deciduous

ERDAS – Earth Resources Data Analysis System

ESRI - Environmental Systems Research Institute

FAO – Food and Agriculture Organization

FCD – Forest Canopy Density

FRA – Forest Resources Assessment

GDP – Gross Domestic Product

GIS – Geographic Information System

GPS – Global Positioning System

GRVI – Green-Red Vegetation Index

MLC – Maximum Likelihood Classification

MLR – Multiple Linear Regression

MRRP – Myanmar Reforestation and Rehabilitation Program

MSS – Myanmar Selection System

MUMD – Moist Upper Mixed Deciduous

NDVI – Normalized Difference Vegetation Index

OLI – Operational Land Imager

RIL – Reduced Impact Logging

SOP – Standard Operating Procedures

SRS – Simple Random Sampling

TM – Thematic Mapper

USGS – United States Geological Survey

UTM – Universal Transverse Mercator

VIR – Visible and Infra-Red

WGS – World Geodetic System

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ABSTRACT

T.Y. Kyaw. The Use of Landsat Imagery and Spatial Analysis to Detect Forest Cover Change and Degradation, and Determine Forest Management Suitability Indices in the Bago Mountain Region of Myanmar, 180 pages, 31 tables, 53 figures, 2018.

The Bago Mountain region in Myanmar is known as the "Home of Teak" (*Tectona grandis*) due to the occurrence of natural teak forests. Nowadays, the composition of this valuable timber species is declining in the region. Thus, the first objective of this study was to quantify forest cover changes between 2000 and 2017. The second objective was to develop GIS models and determine potential sites for reforestation activities. The results revealed that between 2000 and 2017, the annual deforestation rate was 0.78%, and annual forest degradation rate was 1.35%. In addition to reporting the forest cover changes, this GIS land suitability analysis could provide important spatial information for immediate teak restoration planning and investments. The steps employed in this study can be referred to as a protocol for locating candidate sites for reforestation in other geographic areas.

Key Words: Bago Mountain region, teak, forest cover changes, GIS land suitability analysis, reforestation

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CHAPTER 1
INTRODUCTION

Myanmar, located in Southeast Asia, is a country enriched with natural forests. According to the Food and Agriculture Organization (FAO), 58% of the country's land area was covered by forests in 1990. The forested areas abruptly went down to 43% by 2015 (FAO 2015). Although the country has a long history of forest management and still holds extensive forested areas in mainland Southeast Asia, Myanmar has one of the highest rates of deforestation and has been singled out as a deforestation hotspot and the third most deforested country in the world (FAO 2015). In response, in 2016 the Forest Department of Myanmar developed the Myanmar Reforestation and Rehabilitation Program (MRRP) for the period 2017-2018 and 2026-2027. The primary goal of the program is to intensively implement reforestation activities on a national scale. Coupled with the MRRP, the government enacted a nation-wide one-year ban on commercial logging for fiscal year 2016. The logging ban may be extended in the Bago Mountain range (also known as the Bago Yoma) for ten years from 2016 onwards as a special case for conservation. The Bago Mountain range, a major timber-production area in the country, is endowed with naturally growing and high-density teak (*Tectona grandis* Linn. F.) forests; thus the area is known as the "Home of Teak".

1.1. Rationale

Historically, the Bago Mountain range was known as a prestigious forested region due to natural forests dominated by high value teak. The dominant forest type of the Bago Mountain range is mixed deciduous forest, with teak as a major species, along with other hardwood species such as pyinkado (*Xylia xylocarpa*), padauk (*Terocarpus macrocarpus*), and *Dipterocarpus* species, and associated bamboo species such as *Bambusa polymorpha* and *Cephalostachyum* *pergracile*. World-wide, teak is a highly prized wood due to its visual and structural qualities, and thus it is in high demand, in both national (domestic) and international markets. Excessive logging beyond the allowable cut, coupled with land use changes, is threatening the teak resource in this region. Understanding the trends of forest cover change could help forest managers to consider optimal options and actions for required intervention. Spatially-based models providing proposed restoration sites will lead to actual implementation.

The deforestation and forest degradation crisis in the Bago Mountain region is well documented in the literature (Mon et al. 2010; Mon et al. 2012b; Wang and Myint 2016; Win et al. 2009). Previous studies in the Bago Mountain region reported that the forest degradation rate was much greater than the deforestation rate (Mon et al. 2010; Mon et al. 2012b). This attention has led to calls to remedy the situation. However, merely reporting the crisis does not contribute to the restoration of these valuable forest resources. No studies have offered practical recommendations or strategies on how best to reverse this negative trend. It is essential to complement the descriptive studies with research that provides action-oriented protocols to restore the teak forests. In this regard, geospatial analysis is a powerful approach to bridge those gaps and provides a way forward.

The thoughtful application of remote sensing and geographic information system (GIS) analysis can recommend potential sites for forest restoration projects. The results of GIS spatial analysis should be reliable for practical implementation in the field. Thus, a combination of ground reference, GIS, remote sensing, and interviews with local professionals and experts in the study area is required to provide the useful spatial information. In this study, those essential steps were logically conducted. Therefore, the field maps contributed by this study will be immediately useful to develop cost-effective reforestation planning and to engage the required reforestation movement.

1.2. Research Objectives

In this study, land cover maps for 2000 and 2017 were developed to document recent land cover changes. Through change detection analysis, the deforestation and forest degradation were quantified. The aim was to provide spatial maps for forest restoration projects based on the ecological requirements of teak. These general goals were supported by the following study objectives:

(1) To quantify forest cover changes and describe the rates of deforestation and forest degradation between 2000 and 2017,

(2) To locate proposed sites for teak plantations, assisted natural regeneration, and community forestry based on the environmental requirements of teak and practical implications,

(3) To confirm GIS-modeled sites with the local Forest Department to assess its feasibility and accuracy.

1.3. Thesis Structure

This thesis is divided into six chapters. Chapter 1 covers the rationale and research objectives of this study. Chapter 2 includes a review of the relevant literature, consisting of the status and trends of Myanmar's forests, the background of the Bago Mountain range, previous forest cover change detection studies in the Bago Mountain range using remote sensing, and the widespread use of GIS for a variety of land suitability analyses. Chapter 3 covers the methods employed in this study. It consists of the study area description, data acquisition, field work procedures, accuracy assessment, spatial analysis for three reforestation activities, and the steps for obtaining comments from local foresters and comparing with the reforestation plan of the Forest Department. Chapter 4 presents the results, which include satellite image classification accuracy, land cover change figures, rates of deforestation and forest degradation, the GIS-suggested sites for teak plantations, assisted natural regeneration and community forestry, justifications of foresters on re-ranking the GIS site suitability classes and map comparing the results of this study and the Forest Department's plan. Chapter 5 discusses the methods employed and results derived from this study. Justifications and usefulness of this study are also included. Chapter 6 summarizes the outcomes of this study with concluding remarks.

CHAPTER 2
LITERATURE REVIEW

2.1. Nationwide Forest Cover Change Detection

The forests of Myanmar have been dealing with constant pressure from growing resource requirements affiliated with population increase and high wood products demand from adjacent countries (Brunner et al. 1998; Laurance 2007; Mon et al. 2012b). During the period of 1990-2000, the country's foreign earnings depended highly on the export of timber (Mon et al. 2012b) and this trend has continued. Teak (*Tectona grandis* Linn. f.) and other marketable hardwood species are prime drivers of foreign earnings in support of the country's economy (Win et al. 2012b). Among the mercantile timbers in Myanmar, teak has the highest market value due to its durability and workability, reinforced with its impressive resistance to decay and termite attacks (Thein et al. 2007). Even though the forestry sector provided less than 1% of the country's gross domestic product (GDP), timber exports represented around 10% of total exports. Of that 10%, teak made up 60-70% (FAO 2009; Mon et al. 2012a). During 2005-2006 fiscal year, teak exports accounted for $287 million and hardwood exports represented $171 dollars (FAO 2009). Thus, teak has become a principal foreign income source for the nation's economy (Win et al. 2012b).

Based on forest assessments between those situated on the borderline areas and those in mainland parts of the country, Brunner et al. (1998) reported that agricultural expansion, firewood harvesting, and charcoal manufacturing served as the primary drivers of deforestation in the lowland regions of central and lower Myanmar (literally mainland parts), whereas logging was the major factor attributed to the fragmentation of pristine forests in the country's mountainous frontier areas.

Due to these internal and external pressures, the current status of forests is dwindling steadily in terms of both quantity and quality (Htun 2009) despite the fact that the country has a lengthy history of forest management (Win et al. 2009). In spite of its extensive forested areas, Myanmar has one of the highest rates of deforestation in Southeast Asia (FAO 2010; Leimgruber et al. 2005; Mon et al. 2012b; Shimizu et al. 2017). If this trend cannot be curtailed, severe and rapid loss of forest resources will become an inevitable issue in the imminent future (Leimgruber et al. 2005). Myanmar's status as a global deforestation hot spot (Wang and Myint 2016) has attracted considerable remote sensing research focused on forest cover change detection. There is hope that the various scenarios of forest cover change will help natural resource managers and policy-makers to consider optimal options and actions for the required intervention (Win et al. 2009). Empirically based land use and land cover changes could provide the foundation for adaptive forest management (Win et al. 2009).

The Global Forest Resources Assessment (FRA) of the Food and Agriculture Organization of the United Nations (FAO) has conducted worldwide estimates of forest area every 5-10 years since 1948 (MacDicken 2015). The Global Forest Resources Assessment 2015 stated that wealthier countries in higher latitudes had positive trends, but less developed countries in the tropics continue to face serious issues of deforestation and forest degradation (Sloan and Sayer 2015).

Myanmar's forest area was 39.2 million hectares (ha) in 1990, 34.8 million ha in 2000, 33.3 million ha in 2005, 31.7 million ha in 2010 and 29.0 million ha in 2015 (FAO 2015). In terms of annual change rate, it was -1.2% (-435,000 ha/year) during 1990-2000, -0.9% (-309,500 ha/year) during 2000-2010 and -1.8% (-546,400 ha/year) during 2010-2015 (FAO 2015). Hence, there was an average annual change rate of -1.2% (-407,100 ha/year) from 1990 to 2015 (FAO 2015). Consequently, Myanmar was ranked as third in the world in percent forest loss (FAO 2015).

In addition to the FAO's Global Forest Resources Assessment, other studies have addressed forest cover loss in Myanmar, resulting in slightly different figures. Kim et al. (2015) reported that Myanmar had 40.12 million ha in 1990, 39.29 million ha in 2000 and 37.5 million ha in 2010 according to their Landsat-based estimates of forest areas for a 20-year period.

Leimgruber et al. (2005) reported that Myanmar forests have declined by 0.3% annually between 1990s and 2000s which is consistent with the global average. Thus, Leimgruber et al. (2005) argued that there was no evidence to list Myanmar as one of the top ten countries with the highest tropical deforestation, regardless of the FAO (2001a) report.

Htun (2009) reported that Myanmar's forest cover declined from 56% in 1990 to 52.1% in 2000. Between 2001 and 2010, Wang and Myint (2016) found that the total area of deforestation area in Myanmar was 21,178.8 km^2, with a yearly deforestation rate of 0.81% and the aggregate forest carbon release was 20.06 million tons, with a rate of 0.37% annually from 2001 to 2010. In terms of forest types, tidal forests had the highest deforestation and carbon emission rates, and deciduous forests had both the greatest deforestation area and largest amount of carbon liberation (Wang and Myint 2016). These findings corresponded with the FAO report listing five countries (Indonesia, Australia, Myanmar, Madagascar and Mozambique) with the greatest net loss of mangrove forests during the 2000-2010 (FAO 2010). The overall forest loss for all forests in south and southeast Asia was an estimated 67,700 km^2, with an annual loss rate of 0.23% (FAO 2010). Therefore, Myanmar contributed greater than 28% to forest loss in south and southeast Asia even though its land area includes only 7.5% of the entire region (Wang and Myint 2016).

More recently, Bhagwat et al. (2017) found that in 2014, 42 million ha (42,365,729 ha or 63% of Myanmar) was covered by forests using open source software analysis and free access public domain data. They estimated that approximately 38% of the forests have a canopy cover > 80%. However, they reported that the area of intact forests decreased at an annual rate of 0.94%, resulting in greater than 2 million ha in forest loss between 2002 and 2014. They used canopy cover as the break-up to distinguish between intact and degraded forests, and thus > 80% canopy cover as intact forest, 10-80% as degraded forest and below 10% as non-forest.

On the other hand, according to FAO 2015, Myanmar had only 29 million ha (29,041,000 ha) of forest. Hence, there was an enormous difference in estimating the extent of forest cover status. Wang and Myint (2016) suggested re-evaluating the results of deforestation rates by using different datasets and techniques.

2.2. Background of the Bago Mountain Range

The Bago (also known as Pegu) Mountain range is locally known as the Bago Yoma since Yoma is the local term for mountain (Chan et al. 2016). It is a low elevation mountain range, with a maximum elevation of about 800 m above sea level (Bender 1983; Suzuki et al. 2007), running from north to south, with gradual slopes and many mountain streams, located in the central zone of southern Myanmar (Mon et al. 2012a; Win et al. 2012a). The area covers about 2.31 million ha, which represents 3.4% of the total land area of the country (Shimizu et al. 2017). Due to its monsoon climate, three distinct seasons exist: a rainy season from the end of May to November in which, rainfall intensity peaks in July and August, a winter dry season from December to the end of January and a hot dry season from February to May (Win et al. 2009; Win et al. 2012b; Zin 2000). Between 2006 and 2015, the average annual rainfall varied between 2,520 mm and 3,793 mm, and mean annual temperature fluctuated between 13.65° C and 27.42° C (Bago District Working Plan 2016). The average humidity is 82.92% (Bago District Working Plan 2016).

Historically, the Bago Mountain range is a reputed forested zone with naturally growing, high density teak forests (Chan et al. 2013, 2016; Maung and Yamamoto 2008; Mon et al. 2010; Mon et al. 2012a; Win et al. 2009; Win et al. 2012b) -one of the top-quality timber species in the world (Mon et al. 2012a; Palanisamy and Subramanian 2001; Pandey and Brown 2000). In Myanmar, teak is a major species for timber manufacturers and the priority species for plantation establishment projects (Win et al. 2012a). Zin (2000) estimated that the Bago area constitutes 11.3% of all teak-bearing forests in the country. Of the major forest products sourced from natural forests in Myanmar, teak was the most harvested species in the Bago Mountains area (Win et al. 2012b).

The Bago Mountain range commonly encompasses mixed deciduous forests which is the major forest type contributing to commercial timber production in Myanmar (Mon et al. 2010; Shimizu et al. 2017). Tropical mixed deciduous forests, about 38% of the total forest area of the country (Aung 2002; Tun et al. 2016) and approximately 7% of the entire forest area of the world (Htun et al. 2011; Mon et al. 2012a), have a diverse range of deciduous species, occasionally associated with evergreen species (Kermode 1964; Koy et al. 2005; Mon et al. 2012a). Mixed deciduous forests are categorized into two subordinate types: (1) moist upper mixed deciduous forest (MUMD), typified by the observance of bamboos such as *Bambusa polymorpha* and *Cephalostachyum pergracile* and commonly observed on well-drained slopes and fertile soil, and (2) dry upper mixed deciduous forest (DUMD), associated with bamboo *Dendrocalamus strictus* and usually found on ridge tops where solar intensity is unobstructed (Mon et al. 2010; Mon et al. 2012a). *Bambusa tulda* can be observed in the coarse loamy (i.e., can be indented with fingers, but not molded) soil (Kermode 1964; Mon et al. 2010). The best quality teak can be found in MUMD, ideally together with pyinkado (*Xylia xylocarpa*), padauk (*Pterocarpus* *macrocarpus*), taukkyan (*Terminalia tomentosa*) and *Dipterocarpus* species (Khai et al. 2016; Mon et al. 2010; Shimizu et al. 2016; Thein et al. 2007) and similar species grow in DUMD as well (Mon et al. 2010).

In Myanmar, forest reserves were initiated in 1865 (Blanford 1958; Tun et al. 2016). In 1869, human settlements were allowed in the forest reserves of the Bago Mountain range (Chan et al. 2016; Watson 1923). Subsequently, teak plantations were established using the taungya method throughout the Bago Mountains (Bryant 1997; Jordan and J Watanabe 1992; Mon et al. 2012b; Shimizu et al. 2017; Suzuki et al. 2004; Takeda et al. 2005; Yukako 1998). With the taungya system, indigenous people (i.e., Karen people) mainly contributed their efforts to the establishment of the Forest Department's teak plantations in the Bago Mountains. As payment, the Forest Department determined specific shifting cultivation areas for the local people to fulfil their subsistence needs.

2.3. Management of Natural Teak Forests

A selective logging system called the Myanmar Selection System (MSS) has been employed for the management of natural teak-bearing forests in the Bago Mountains since 1856 (Gyi and Tint 1995; Mon et al. 2012b; Shimizu et al. 2017; Win et al. 2009; Win et al. 2012a). MSS is regarded as a means of ensuring the sustained yield of teak. Directional felling towards bamboos and combined with elephant skidding result in reduced impact logging (RIL), causing the lowest level of damage to residual trees and soil (Khai et al. 2016; Khai et al. 2016). Selective logging applies the principle of felling the most valuable and desirable timber species in natural forests whilst the residual stands are kept for continued growth in their natural way over a period of time (Bawa and Seidler 1998; Win et al. 2009). According to MSS, marketable trees beyond a pre-determined diameter limit are selectively thinned on a 30-year felling cycle.

The annual allowable cut (AAC) is estimated from periodic timber cruises (Gyi and Tint 1995; Mon et al. 2012b; Shimizu et al. 2017; Win et al. 2009; Win et al. 2012a; Win et al. 2012b). In Myanmar, the AAC prescribed in the MSS fluctuates from 15 to 19 m^3/ ha (FAO and UNEP 1984; Mon et al. 2012b; Thwin and Han 1991).

Despite the fact that selective logging is the principal practice for achieving sustainable forest management, it may alternatively be a menace to sustainability (Bhandari 2003; Win et al. 2012b). Even though only fragmentary disturbance of the forest structure takes place, selective logging can alter the forest canopy, biomass and species (Johns et al. 1996; Schulze and Zweede 2006; Win et al. 2012b). Therefore, Win et al. (2009) advised that more research was needed on species composition, diversity, and successional forest structure following selective logging operations.

In spite of drawbacks, the MSS is still the main silvicultural system formulated to manage the natural teak forests in the country (Win et al. 2009). In the study of three reserved forests of the central Bago Mountain range for the period of 1989-2006, Mon et al. (2012b) highlighted that the felling cycle had been shortened recently to approximately 5-15 years in readily accessible forests. Heavy reliance on foreign income from timber exports resulted in a shorter felling cycle, leading to over-exploitation and abandonment of the annual allowable cut (Brunner et al. 1998; Htun 2009; Mon et al. 2012b). Mon et al. (2012a) revealed that timber harvesting was carried out in 218 of 323 compartments in the three reserved forests of the central Bago Mountains during 1989 and 2009, and 119 compartments were logged more than two times within 20 years, indicating that those compartments were over-exploited, which violates the MSS rule of 30-year felling cycle. During that 20-year period, timber volume extractions ranged from 0.11 to 53.49 m^3 ha^{-1}. A study by Khai et al. (2016) also confirmed that repeated logging at shorter intervals occurred in the two compartments of the South Zamayi reserved forest of the Bago Mountain range. The development of logging roads improved accessibility which expedited illicit cutting of not only timber species, but also non-timber species for charcoal production. The authors advocated for a return to the 30-year cutting cycle to ensure sustained yield, and to close the logging roads after logging to discourage illegal logging.

Due to the decline of forested areas, the government of Myanmar legislated a one-year logging ban across the entire nation in 2016 and for 10 years in special regions (Shimizu et al. 2017). Since then, timber harvesting in the Bago Mountain range has been prohibited for 10 years. On the other hand, Shimizu et al. (2017) was skeptical that the harvesting ban could effectively remedy the forest health issues because in addition to selective logging, other physical disturbances such as dam construction and shifting cultivation could further contribute to deforestation in Myanmar. However, Brown et al. (1994) and Mon et al. (2012b) maintain that shifting cultivation does not play a chief role in causing deforestation if a fallow period (i.e., resting period after agricultural cultivation) is kept long enough.

2.4. Quantifying Loss of Forests in the Bago Mountain Range

Due to the advancement of monitoring technology and field surveys, time series satellite images over extensive areas could aid in understanding the historical disturbances that affect the ecosystems of forest biomes (Romijn et al. 2012; Romijn et al. 2015; Shimizu et al. 2016). There are many studies emphasizing deforestation in the tropics using remote sensing tools (Chowdhury 2006; Fuller 2006; Steininger et al. 2001; Win et al. 2012b). Remote sensing is a widely recognized technology to mass-produce timely information for forest management (Win et al. 2012b). Remote sensing images were extensively used to track forest cover changes (Coppin and Bauer 1996; Fraser et al. 2005; Hame et al. 1998; Panigrahy et al. 2010; Win et al.

2012b). Forest disturbances due to anthropogenic actions or natural phenomena, or both, can be remotely monitored and evaluated using cutting edge geospatial analytics (Sadar et al. 2003; Win et al., 2012b). Shimizu et al. (2016) affirmed that time series Landsat images combined with trajectory-based analysis could be used to detect forest disturbances such as selective logging in selectively cut forests of Myanmar. The trajectory-based analyses (Hermosilla et al. 2015; Huang et al. 2010; Kennedy et al. 2007; Kennedy et al. 2010; Verbesselt et al. 2010; Verbesselt et al. 2012) and classification-based analyses (Griffiths et al. 2014; Grinand et al. 2013) are considered as the achievable modi operandi (Shimizu et al. 2016). There are a good number of image classification techniques applicable to estimate forest canopy density (FCD) via satellite data such as visual interpretation, object-based classification, maximum likelihood classification, linear regression, FCD Mapper and artificial neural networks (ANNs) (Chandrashekhar et al. 2005; Joshi et al. 2006; Mon et al. 2012a; Nandy et al. 2003; Nangendo et al. 2007; Panta et al. 2008; Rikimaru 1996; Roy et al. 1996). Shimizu et al. (2017) and Shimizu et al. (2016) used trajectory-based analysis to determine forest disturbances in the Bago Mountain region. In addition, there was also previous research investigating the forest cover conditions of the Bago Mountain region using pixel-based image classification.

With the aid of geospatial techniques, Shimizu et al. (2017) examined the entire Bago Mountain region to understand the disturbance agents attributed to the forest change using a Landsat Time Series for the period of 2001-2013. The trajectory-based analysis of Shimizu et al. (2017) found that logging was responsible for the largest area of disturbance, followed by flooding due to dam construction, shifting cultivation, plantation establishment and urbanization in this tropical forest. They provided an approach to map disturbance areas, disturbance agents, and subsequent recuperation efforts in the Bago Mountains. According to their findings, even though such disturbances as logging, plantations and shifting cultivation existed, a considerable amount of forest restoration, which brought about 9.1% of the forest cover in the region, took place due to the follow-up recovery of forests. Win et al. (2009) agreed with that claim that shifting cultivation might not contribute to high-level deforestation. For shifting cultivation, the slash-and-burn method is carried out as a site preparation. Afterwards, annual/seasonal agricultural crops are cultivated for a few years. The same process shifts to another forested area again and again, using the same method for cultivation. During that period, the previously unused (i.e., already harvested) areas can recover to forests provided that the fallow (resting) period is kept long enough.

Shimizu et al. (2016) also investigated forest disturbance resulting from selective logging using the Landsat time series image during 2000 and 2014 integrated with trajectory-based analysis. For detecting the forest changes, they used the LandTrendr algorithm (Kennedy et al. 2010) for the Landsat time series stack (Shimizu et al. 2016). They selected Yedashe, Taungoo, Oktwin and Phyu townships in the Taungoo district (part of the Bago Mountains) which have an area of 139,000 ha. They evaluated the accuracy of forest disturbance monitoring on a yearly basis using a trajectory-based Landsat time series analysis and pinpointed the location and total areas of intervention caused by selective felling as referenced by existing annual logging records with logging year and number of trees harvested. Their results revealed that they attained 83.0% as an overall accuracy of forest disturbance detection yielded from the validation samples, and the areas impacted by selective logging was 4.7% and other disturbance factors made up 5.4% of the study area. The authors suggested that trajectory-based analysis could be a protocol, but cautioned against investigating disturbances due to the possible incidence of detection errors. To determine errors with respect to selective felling detection, they carried out an analysis at a compartment-scale instead of a pixel-scale since there was a dearth of elaborate information of logging actions at the pixel level. Due to observing few commission errors for disturbance detection, but big omission errors for each disturbance year, they recognized that there was an underestimation of disturbance detections. According to their finding, the immerse disturbance was observed in 2010, while the greatest disturbance associated with selective felling took place in 2011. On the other hand, they acknowledged that there were limitations on disturbances data except selective logging. Thus, they recommended additional studies investigating the causes of disturbances except selective logging, and the potential future consequences to complement their research.

There was also other research focusing on portions of the Bago Mountains through selecting some of the reserved forests within the region. Mon et al. (2012b) selected three reserved forests (Khapaung, also spelled as Kabaung, Middle Nawin and South Nawin) within the Bago Mountains region to determine factors contributing to deforestation and forest degradation in production forests where selective logging was practiced. They employed forest canopy density maps generated from Landsat images for 1989 and 2006, alloying to ecological considerations, localized factors and logging records in regression models. Based on the definitions of FAO (2005), they classified forest canopy density (FCD) maps into non-forest (FCD < 10%), open forest (FCD 10-40%), and closed forest (FCD > 40%). Using the canopy cover as the index, they defined deforestation as the conversion from forest to non-forest category; and forest degradation as the conversion from closed to open forest category. Their study published that elevation and distance to the nearest town strongly impacted the threat from both deforestation and forest degradation, whereas logging and vicinity to the nearest village were related with the occurrence of forest degradation only, not deforestation. They suggested that it might be due to the minimized use of heavy machinery in timber extraction in their study area. Elephant logging is a typical practice in Myanmar which reduces impacts to the forest (Dah 2004; Mon et al. 2012a; Win et al. 2009; Win et al. 2012b). Win et al. (2012b) reported that elephant logging may lessen the ground damage from the construction of skid trails because animals could perform skidding from the stumps to the landing areas. It implies that skidding logs can be handled by elephants, which reduces negative impacts to the soil and residual stands (Brunner et al. 1998; Shimizu et al. 2016). Elephants can skid logs within a 1 m width of pathway, and thus, it is not required to make small roads or tracks (Win et al. 2012b). Selection logging operations are commonly completed during the later days of January, but other operations (e.g., skidding) may be accomplished as late as February (Shimizu et al. 2016). Mon et al. (2012b) also asserted the point that as long as selective logging intensity strictly followed the allowable cut recommended by MSS, forest degradation could not happen. Thus, they suggested maintaining the logging intensity below the AAC because exceeding beyond the quota of MSS could significantly foster forest degradation. Additionally, they provided a warning that deviating from the AAC limit could result in forest degradation and then deforestation on condition that recurrent loggings were conducted in the same area of forest. Kanninen et al. (2007) corroborate the claim of Mon et al. (2012b) that selective logging does not lower the forest canopy cover to less than 10%, a widely accepted minimum threshold to differentiate forest from non-forest. In addition, they further contend that selective logging alone did not seem to be the key contributing factor for forest degradation in areas having lower intensity of logging. Instead, they concluded that shifting cultivation or illicit cutting or probably both may be the cause of forest degradation in their study area. Shifting cultivation is regarded as a primary disturbance causing deforestation and forest degradation. Since 1991, such practices contributed to 61% of worldwide tropical forest destruction (Chan et al. 2013; Karthik et al. 2009).

Using Landsat 7 imagery acquired on 15 January 2006, Mon et al. (2012a) compared three image classification approaches – maximum likelihood classification (MLC), multiple linear regression (MLR) and forest canopy density (FCD) mapper to estimate the FCD in the three reserved forests of the central Bago Mountains- Khapaung, Middle Nawin and South Nawin which cover an area of 2,700 km^2. Their primary research objective was to select the most effective image classification method for estimating the FCD. They grouped the FCD into four classes: closed canopy forest (FCD ≥ 70%), medium canopy forest (40% ≥ FCD < 70%), open canopy forest (10% ≥ FCD < 40%) and non-forest (FCD < 10%). They found that the FCD mapper method provided the highest overall accuracy, followed by MLC and MLR.

Mon et al. (2010) used the FCD mapper and multi-temporal Landsat images (1989, 1999, 2003, and 2006) to understand the historical trends of both deforestation and forest degradation in the same study site as Mon et al. (2012b). They achieved an overall accuracy of 81%. During that time span of 17 years they declared that greater than 90% of the study area was deemed as forests (i.e., FCD ≥ 10%), whereas closed canopy forests (FCD ≥ 70%) markedly declined from 98% to 53%. Conversely, they found that medium canopy forests (40% ≤ FCD < 70%) and open canopy forests (10% ≤ FCD < 40%) enlarged. They reported that there was a high yearly net forest degradation (conversion to lower FCD) rate of 2.5%, despite a comparatively low yearly net deforestation (forest to non-forest) rate of 0.2% during 1989 and 2006. According to their analysis, the problems of forest degradation ran far ahead of deforestation and follow-up research of desirable species and succession would definitely be required. Due to the significant rate of forest degradation, they were concerned about the future sustainability of forest resources in the area.

Win et al. (2009) also conducted an assessment of forest cover changes and their causes for 1989, 2000 and 2003 in the Kabaung reserved forest, which was one of the reserved forests in the Bago Mountain range, by integrating satellite image analysis with field observations, interviews and logging records (such as felling year, logging compartment, number of trees harvested, total volume of trees cut, and species name). In their study area, selective logging was the usual practice. They selected training samples for generating forest cover maps for 1989, 2000 and 2003 through field inspection, local interviews and information accessed from the Forest Department. They completed supervised classification in ERDAS Imagine using the maximum likelihood algorithm. During image classification, they considered the area, shape, and chronological discrepancies in plant cover for the recognition of shifting cultivation plots. In their study area, they categorized the forest cover classes as forest, degraded forest (bamboo), bare land and grassland, and water. In order to discern the selective logging areas, they used an integration of supervised classification and normalized difference vegetation index (NDVI) image differencing. They found that intensive cutting prior to dam construction was a key factor for deforestation among the four underlying causes such as selective logging, dam construction, shifting cultivation and teak plantations establishment. Their study claimed that selective logging in accordance with MSS did not significantly impact forest cover change and deforestation. In the case of readily reachable non-logging compartments, they stated that illicit felling was the possible catalyst for forest cover changes. Based on their interviews with local people, farmers might favor degraded forests (bamboo) for shifting cultivation due to easier conditions for site preparation. In their study area, teak plantations were established using the taungya method (i.e., planting teak seedlings with agricultural crops) to restore the forest resources. It is a win-win strategy, allowing farmers to contribute to reforestation activities of the Forest Department while simultaneously providing an opportunity to cultivate intercrops in the form of agroforestry for the initial years of establishment (Suzuki et al. 2007; Win et al. 2009).

Win et al. (2012b) returned to the same area of Win et al. (2009) (Kabaung reserved forest) to assess forest degradation and forest cover change due to selective logging using remote sensing techniques. Using NDVI image differencing, they conducted a pixel-based analysis during the period of October 2007 and January 2009 by using two SPOT-5 pan-sharpened images acquired during the period of selective logging and by field inspections. They completed fieldwork from November 2008 to January 2009 in areas where selective logging had occurred in September 2008. As confirmed by field observations, there was some leaf drop in January, but for the most part, trees kept their leaves. Hence, they affirmed that the spectral signature difference should not be that much between images of October (rainy season) and January (end of cold dry season). In addition, they warned that future harvesting of teak was not sustainable because teak trees representing the smallest diameter class, 10-20 cm diameter at breast height (DBH), were lacking. They found that NDVI differences were significant in most logging roads and landing sites, but in most unlogged areas, there were small changes. They also observed that the spectral differences between before and after harvesting indicated that logging roads had a more significant impact on canopy changes than teak stumps.

All in all, it can be deduced that forest loss is happening in the Bago Mountain region. Despite the fact that different methodologies were developed to quantify deforestation of this historic area, there was a scarcity of action-oriented studies conducted to restore the degraded environment.

2.5. The Bago Mountain Range – A Research Repository?

In addition to investigating changes in forest cover using remote sensing and GIS tools, the Bago Mountains have hosted a wide variety of studies. Tun et al. (2016) highlighted the critical role of forest management and protection level due to their respective influences on maximizing the carbon storage potential and enriching the diversity of large trees through their study in both reserved and public mixed deciduous forests, namely, Khabaung reserved forest, Kyaukmasin reserved forest and Yoma protected public forest. They found that large tree diversity was predominantly higher in two reserved forests (which had limited access and prohibitive rules for public harvesting of forest products) compared to protected public forest (which was aimed for public use and regulated logging). They assumed that illegal logging contributed to the reduction of carbon stocks in the protected public forest. Thus, they declared that the degree of forest protection should be taken into account as a key component in carbon accounting.

Chan et al. (2013) established new allometric models for the estimation of above-ground biomass in fallow forests, following shifting cultivation, around a Karen village (S village) situated in the Bago Mountain. In the same study site, Chan et al. (2016) conducted an assessment to improve the understanding of above- and belowground biomass and carbon stocks as well as soil carbon buildup in shifting cultivation forests.

Within the Oktwin township of the Bago Mountain region, measurements of fallow vegetation and total carbon and nitrogen after shifting cultivation, and comparison of those results with those in natural teak forests disturbed by selective logging were implemented by Fukushima et al. (2007). Their objective was to improve the understanding about the recovery period of fallow vegetation. They found that a long fallow period of over 12 years was required after a one-year cultivation to maintain a sustained swidden cultivation (in other words, shifting cultivation) in the Bago Mountain range.

Suzuki et al. (2004) examined the impact of forest fires on taungya teak plantations in two reserved forests of the Bago Mountains, namely, Kabaung and Bondaung where teak reforestation has been implemented since 1884. They found that combustion of the forest floor litter by forest fires impeded the accumulation of soil organic matter, especially by the time the forest fire season coincided with the leaf shedding season of teak. Thus, they concluded that the long-term sustainability of taungya teak regeneration might be threatened by the outbreak of forest fires. That conclusion is much more pragmatic particularly if forest floor litter content (i.e., the main source of soil organic matter) cannot be sufficiently maintained.

In the same area, Suzuki et al. (2007) concluded that even after forest fire disturbance, Ca (i.e., a dominant mineral nutrient in teak leaf litter) could stay in the ash because the volatilization temperature of Ca is generally greater than peak temperatures of a forest fire. Thus, they highly recommended for the conservation of leaf litter in teak plantations.

Again, within the same study site, Suzuki et al. (2009) studied the impact of burning the bamboo forests during the slash-and-burn and following intercropping periods of taungya teak reforestation with a peculiar interest on the effect of ash incorporation on nutrient cycling.

Through a case study on the eastern part of the Bago Mountain range, Tani (2000) highlighted the influences of ecological factors (such as topography and water conditions) in recruiting taungya farmers who serve as the major labor source for teak reforestation. Win et al. (2012a) tried to understand whether ongoing logging practices boosted the regeneration of two commercial tree species, such as teak and pyinkado, by means of comparing shooting densities in sites intervened by logging activities. Their results showed that the density and growth performance of recruited teak shoots were not apparently different between logged areas with felling gaps (i.e., areas with more light availability) and unlogged areas. Therefore, they had perceived that felling gaps created by selective logging may be insufficient for the enhancement of teak regeneration in the Kabaung reserved forest of the Bago Mountains. They suggested implementation of silvicultural operations that could generate more sunlight and create favorable conditions for teak regeneration to compete with other undesirable vegetation.

Using remote sensing and GIS, Hlaing et al. (2008) pinpointed the priority soil conservation watershed spots based on the status of soil loss (obtained from Universal Soil Loss Equation) and morphometric indices for the Bago river basin. Maung and Yamamoto (2008) aimed at evaluating the obtainable socio-economic benefits of plantation villagers through a case study in three plantation villages located on the eastern slope of the Bago Mountain range. They reported that the Forest Department of Myanmar should shift from relying mainly on foreign earnings through the extraction of teak plantations to resolving deforestation through the engagement of rural populations.

Within the Kabaung reserved forest of the Bago Mountain area, Thein et al. (2007) observed that the occurrence of bamboo flowering (bamboo dies after flowering) overlapped with the logging actions and such conditions favored the accelerated height growth of the saplings to recruit the pole size class. Nevertheless, logging or bamboo dieback alone could not give an obvious result. They reported that 84-96% of tree saplings dominated the bamboo seedlings in bamboo flowering areas with logging, but there was only a range between 53% and 56% in areas with no logging.

Through field evidence, Khai et al. (2016) verified that forest degradation happened in the South Zamayi reserved forest (i.e., part of my study site) of the Bago Mountain region. They compared stand structure, desirable species and bamboo composition, and the occurrence of illicit cutting between two compartments with different logging intensities and frequencies.

Through reviewing the aforementioned work, it is fair to say that the Bago Mountains area is a compelling region for research for a wide range of interesting studies. Among the many topics, deforestation and forest degradation are the most challenging to address in recent history.

2.6. Using GIS for Site Suitability Analyses

To my knowledge there was no prior published scientific paper with reference to a combined approach of remote sensing and GIS techniques for determining the optimal areas with suitability indices for the purpose of teak or any other species restoration in the Bago Mountains. Thus, most references were associated with research outside the territory of Myanmar. However, it is good to review the protocols applied to such land suitability analyses based on environmental and multi-criteria requirements. There are a good number of published papers using GIS as dependable tools for determining the possible areas for initiating restoration endeavors or other suitability analyses.

Using GIS, Muñoz-Flores et al. (2017) determined potential areas for the establishment of commercial forest plantations of *Tabebuia rosea* (Bertol.) in Michoacan, Mexico where the area highly required reforestation. Considering the ecological requirements of the target species such as precipitation, temperature, soil type, elevation, land use and slope, they outlined the potential areas. They generated two maps: one in accordance with a slope specification of 0-15% for non-manual forest plantations and the other one based on a slope range of 15-30% for manual forest plantations.

By combining remote sensing data (30-m spatial resolution) and geospatial analytics, Aguirre-Salado et al. (2015) successfully modeled land suitability sites for the set-up of commercial tree plantations in the Huasteca, Mexico with six species, namely, *Tectona grandis*, *Eucalyptus grandis*, *E. urophylla*, *Gmelina arborea*, *Cedrela odorata* and *Acrocarpus fraxinifolius* using a multi-criteria/ multi-objective approach. They stated that their proposed methodology can be referenced as a protocol in other areas of the world for assessing multi-objective land suitability analyses for industrial tree plantations. Using a weighted linear integration method and considering environmental requirements of the relevant species such as climate, soil, topography and land availability factors, they generated land suitability maps for individual species which could be contributed as a landscape planning tool to decision-makers.

Webb and Thiha (2002) investigated how alloying socio-economic data to biophysical parameters into GIS resulted in better site selection methods for forestry and conservation movements in the Kyaukpadaung Township, which is located in the dry zone area of central Myanmar. Using forestry activities as an example, they reported that GIS-assisted planning could be improved through the integration of social suitability (such as perceptions and priorities of local people towards reforestation activities) into the biophysical suitability (such as land use/land cover, slope and accessibility) even though such integrated methods to land use planning were not novel.

Jaimes et al. (2012) simulated models that could locate optimal zones for forest plantations meeting three principal objectives: commercial production, restoration and protection, and agroforestry in the state of Mexico. They used GIS integrated with multi-criteria spatial analysis techniques to simulate future scenarios. Their results could prove useful to territorial managers and planners as it included information about the current status of forest cover and future reforestation outlines.

In addition to forestry examples, there are also other suitability analyses. Li and Nigh (2011) used GIS to rate private land parcels for biodiversity conservation based on multiple factors such as land parcel size, forest area, stream corridor area, distance to public lands and roads and heritage records (presence of endangered species). They applied a scoring approach with subjective weighting. Their GIS model provided spatial information displaying priority land parcels in the Current and Eleven Point Hills Conservation Opportunity Areas of southeastern Missouri Ozarks. Like Aguirre-Salado et al. (2015), they claimed that their methodology could contribute potential applications to other corresponding priority areas.

Widiatmaka (2016) delineated suitable and available land for tropical high-altitude vegetable crops with the help of GIS, multi-criteria decision-making for land evaluation and remote sensing in Puncak in Java Island, Indonesia. He designated priority lands that should be prevented from non-agricultural land use so as to ensure the sustained yield of vegetables, and such analysis would be constituted as a database for horticulture land use planning.

Ahmad et al. (2017) created a nutrient availability and agroforestry suitability map in the open land area of Chakardharpur subdivision of West Singhbhum district of the Indian State of Jharkhand using geospatial tools. They verified with field inspection in watersheds based on agroforestry suitability ranks and cross-checked by Google Earth. Through their study, they believed that the use of supplementary data in GIS software could possibly locate the optimal locations up to the village level.

Kar and Hodgson (2008) proved that a GIS-based model can be used for other projects like allocating suitable hurricane emergency evacuation shelters. They ranked the current and candidate shelters such as schools, colleges, churches and community centers obtainable in the

17 counties of Southern Florida depending on their site suitability. They developed a GIS model integrating Weighted Linear Combination with a Pass/Fail filtering method.

Hence, GIS can be used as a powerful tool for the selection of optimal sites for reforestation, biodiversity conservation, agricultural expansion and other land suitability related studies.

CHAPTER 3
METHODS

3.1. Study Area

The study site consists of four reserved forests, Baing Dar, Kawliya, Shwe Laung Ko Du Gwe and South Zamayi, located on the eastern slope of the Bago Mountain range (Figure 1) of Myanmar. Located at approximately 17° 37' - 18° 08' N, 96° 00' - 96° 31' E and situated in Kyauktaga, Bago and Daik-U townships of Bago District, the study area has a total area of approximately 175,967 ha (Table 1). The elevation ranges from 26 m to 734 m. Teak growing in the Bago Mountains provides top-quality timber in Myanmar and the study area is recognized as one of the best teak forests in the country. Due to past exploitation, the government of Myanmar enacted a 10-year commercial logging ban in the region in 2016.

Table 1. Study site (Source: Remote sensing and GIS section of the Forest Department)

Reserved Forest	Estimated Area (ha)	No. of Compartments	Township
Baing Dar	38,669	111	Bago
Kawliya	35,761	151	Bago
Shwe Laung Ko Du Gwe	21,827	121	Kyauktaga
South-Zamayi	79,710	119	Daik-U
Total	175,967		

3.2. Methods of Selecting Study Site

According to the literature and professional observations, it was evident that the Bago Mountains have been facing deforestation and forest degradation issues. As described in the objectives, this study seeks to quantify changes in forest cover status with respect to deforestation and degradation, and to follow up with recommendations for candidate teak reforestation areas. Prior consultation with Myanmar Forest Department officials provided assurance that the study site was suitable to achieve the objectives of this research. Based on the recommendations of the experts from the Forest Department, the aforementioned four reserved forests were selected as the study site. The study area also fell within one Landsat footprint, which simplified image classification.

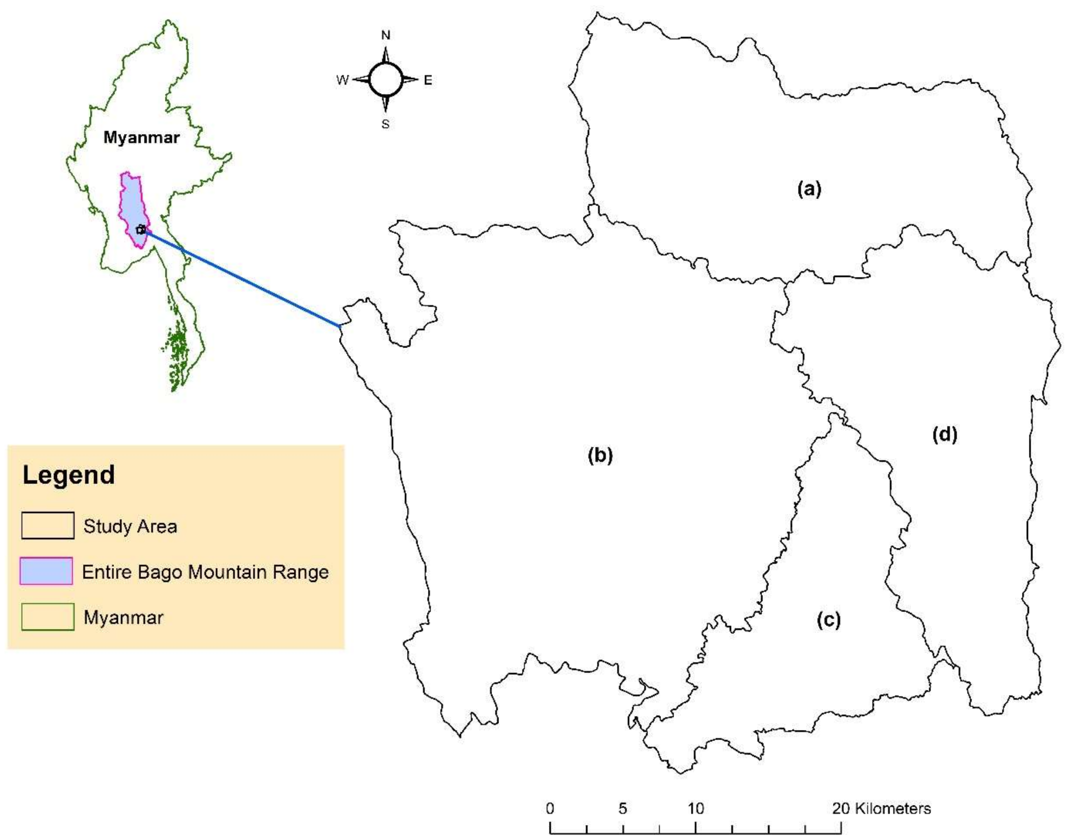


Figure 1. Location of the study area. The study area consists of four reserved forests, namely, (a) Baing Dar, (b) South Zamayi, (c) Shwe Laung Ko Du Gwe, and (d) Kawliya. The study area is part of the Bago Mountains region.

3.3. Forest Cover Change Detection

3.3.1. Data

Landsat images with less than 10% cloud cover were acquired from the United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov) to generate land cover maps and to quantify the forest cover changes between 2000 and 2017. The study area completely fit in one Landsat footprint (path 132 and row 48). Landsat Collection 1 Level-1 data containing reflectance values were used for image classification.

For the 2000 image, a Landsat 5 TM Collection 1 Level 1 image, acquired on December 17, 2000, was used. For the 2017 image, a Landsat 8 OLI Collection 1 Level-1 image, acquired on January 30, 2017, was used. The georeferencing was set to WGS 1984, Universal Transverse Mercator (UTM) coordinates in zone 47 N. UTM is the official coordinate system used by the Forest Department, and that coordinate system would be consistently applied throughout the analyses.

3.3.2. Field Inspection and Ancillary Data

Within the study area, ground inspection was carried out during May and June of 2017. Coordinates and associated land cover types were marked with a Global Positioning System (GPS) receiver. Land cover types were grouped into five classes: forest, degraded forest/ bamboo forest, other wooded land, other land and water body (Table 2). GPS points were recorded as follows: 36 points for forest, 73 points for degraded forest/ bamboo forest, 51 points for other wooded land and 21 points for other land (Figure 2). Such recordings were carried out in the middle of the specific land cover types so that those GPS points and their associated land cover features could be easily distinguishable during image interpretation. Those GPS points would be used as training data for the remote sensing classification. No reference points were collected for water as it was easily discernible in the imagery. During field visits, photos were taken to visually improve the understanding of specific land cover types (Figure 3).

The GPS receiver was the primary tool for indicating and recording the locations, but there were some constraints. To overcome those limitations, Google Maps installed in the iPhone was used to verify land cover types while ground truthing. Like the GPS, it could navigate to specific locations. The GPS could only guide me to the selected locations of the cover types to confirm and locate in the field. The overriding advantage of using Google Maps was that the underlying land cover types with associated assorted color tones could be deciphered on the iPhone because it displayed the colorful base map. This method was simple but very practical, and it could deliver a great deal of valuable information in deciphering the land cover types of the study area.

The combination of field points and local forester interviews provided the preliminary information about the land cover conditions of the study area. Further consultations with a GIS/remote sensing expert from the Forest Department were used to improve the quality of work.

Table 2. Definition of land cover types

Land Cover	Definition
Forest	Land where trees dominate but in association with bamboo. Bamboos found in this land are larger in size than those of degraded forest/ bamboo forest.
Degraded Forest/ Bamboo Forest	Land with a dominant proportion of bamboo, combined with small trees and a few large trees. Degradation here does not mean diminishing site quality but simply implies that it has fewer large trees. It is recognized as “forest” in this study.
Other Wooded Land	This land cover is not recognized as forest. It includes scrubland, bushes, young plantations and taungya shifting cultivation.
Other Land	All the land that is not defined as forest, degraded forest/ bamboo forest and other wooded land. It includes roads, agriculture, open/bare soil, settlements, and infrastructure.
Water Body	Streams and water reservoirs including dams.

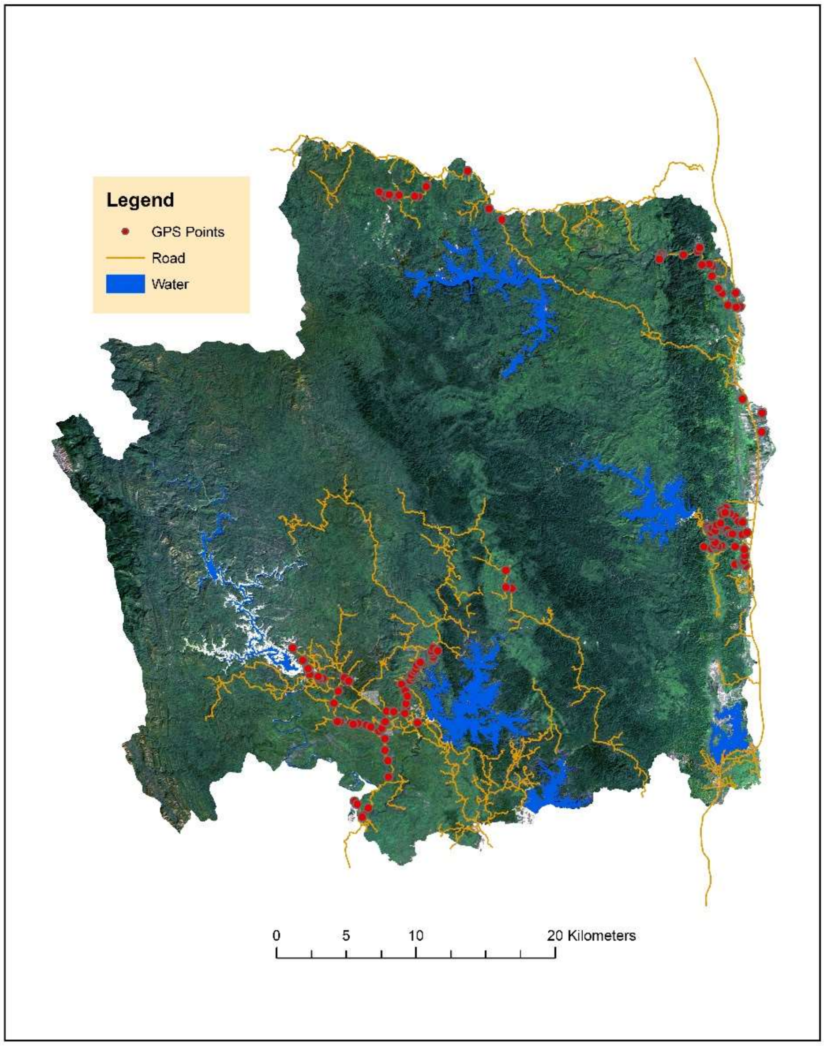


Figure 2. Locations of recorded GPS points on top of 2017 Landsat image

(a)

(b)

(c) (d)

Figure 3. Land cover photos (a) Forest, (b) Degraded forest/ Bamboo forest, (c) Other wooded land (scrubland), and (d) Other land (road)

3.3.3. Supervised Image Classification

Image classification was conducted with ERDAS Imagine 2016 (Hexagon Geospatial). As pre-processing steps, bands 1 to 7 from the 2017 Landsat 8 image were stacked and similarly, bands 1 to 5 and 7 from the 2000 Landsat 5 image were stacked. Then, the images were clipped to the extent of the study area. A flowchart explaining the image classification steps is illustrated in Figure 4.

Supervised classification using the maximum likelihood algorithm was used for both 2000 and 2017 images. Five categories of land cover were classified; 1) forest; 2) degraded forest/bamboo forest; 3) other wooded land (including scrubland, bushes, young plantations and shifting cultivation); 4) other land (including roads, agriculture, open/bare soil, settlements, roads and infrastructure); and 5) water body.

Providing training samples was a required step for supervised image classification. As stated earlier, prior to software manipulation, ground truthing and GPS marking about unique land cover types immensely helped in selecting the optimal training samples to avoid confusing land cover classes. In addition to field knowledge through GPS recordings, the texture, pattern, site, color and local knowledge were used as clues for satellite image interpretation. Furthermore, local interviews and supporting documents, Google Earth Pro was useful in identifying the objects, especially for the 2017 image. Although the Landsat image offered 30 m ground sampled distance, Google Earth Pro was an excellent reference as it provided high-resolution Centre National d'Etudes Spatiales (France) (CNES)/Airbus imagery of the region for 2017, which greatly helped in distinguishing land cover types.

A total of 140 training samples (Table 3) was selected to generate a classified map for 2017 in the ERDAS Imagine. Polygons were used to select appropriate training samples. To include all land cover types, polygons representing various and unique land cover features were carefully selected and applied as training samples.

To interpret the 2000 image, the formerly classified 2017 land cover map was used as the reference because the ancillary data which could help interpret the historical 2000 image was not available. A total of 123 training samples (Table 3) was selected to obtain a classified land cover map for 2000.

After supervised classification, recoding was followed to reclassify the resultant land cover classes in a well-organized way. Ideally, the classified image after recoding looked salt-and-pepper appearance due to the inherent variability of the spectral characteristics (Bischof et al. 1992). Therefore, for post-classification smoothing, neighborhood tool available in ERDAS Imagine was applied to smoothen the classified image. The 3x3 window was used as the size of the focal kernel to filter the majority.

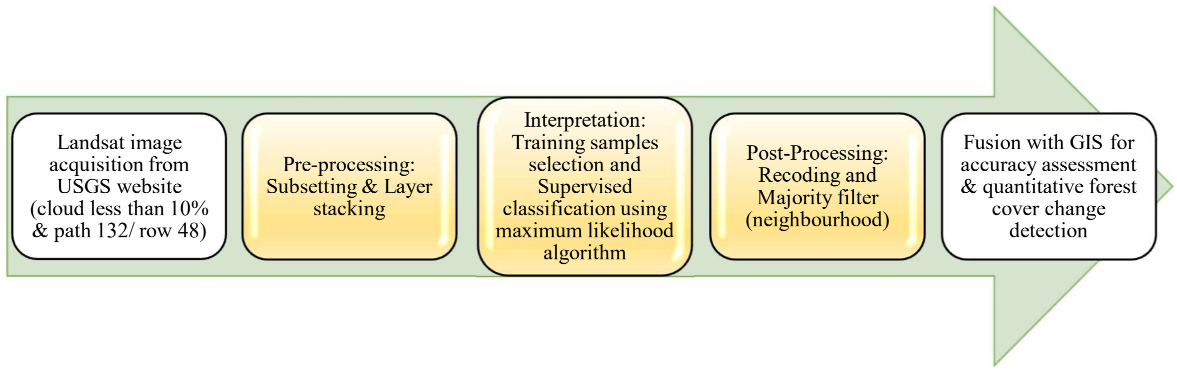


Figure 4. Satellite image classification protocol

Table 3. Number of trainings samples applied for the supervised classification of both 2000 and 2017 images

Land Cover Category	**Training Samples for 2017**	**Training Samples for 2000**
Forest	27	32
Degraded Forest	54	15
Other Wooded Land	16	12
Other Land	14	32
Water Body	29	32
Total	**140**	**123**

3.3.4. Assessing Image Classification Accuracy

In remote sensing studies, land cover maps generated by classification should be evaluated by assessing their accuracy. For pixel-based accuracy assessment, there are four basic sampling designs- simple random sampling (SRS), systematic sampling, stratified random sampling, and cluster sampling (Stehman 1999; Stehman and Foody 2009). In this study, stratified random sampling was used to satisfy the objective of precisely estimating class-specific accuracy (Stehman and Foody 2009) because interest levels among land cover types were not the same.

The ArcMap 10.4.1 (ESRI; Redlands, CA) was used to create a total of 310 points for accuracy assessment. The first three land cover classes were given a higher priority; thus, 20 more points were added to those classes in assessing classification accuracy. Hence, 70 points were created for the forest, degraded forest/bamboo forest and other wooded land (which were aimed at later use for GIS site suitability analyses) classes while 50 points were created for other land and water body (i.e., less important land cover classes).

To create stratified random points in ArcMap environment, “Create random points” tool was used. A new column was added in the attribute table using “add field” and the desired number of random points were manually provided (i.e., edited) for each land cover type. Afterwards, the stratified random points created in ArcMap were imported into Google Earth Pro to investigate the classification accuracy for both 2000 (Figure 5) and 2017 (Figure 6). Then, to report the error matrix, the accuracy measures formulas presented by Stehman and Foody (2009) were used (Table 4). In addition, to estimate the variance, the stratified random sampling formulas of Stehman and Foody (2009) were applied in this study (Table 5).

To assess the accuracy of the 2017 classified map, the high-resolution CNES/Airbus image (accessed on June 20, 2017) available at the Google Earth Pro was used. Furtuna et al. (2016) used high-resolution image available on Google Earth for assessing classification accuracy during their forest area change detection analysis using remote sensing and GIS tools. The Forest Department of Myanmar also relied on Google Earth Pro as a reference for accuracy assessment.

Table 4. Formulas for accuracy assessment (Stehman and Foody 2009)

Characteristic	Population	Stratified Random Sampling
Proportion of area in cell (*i, j*)	p_{ij}	$(n_{ij}\, N_{i+})/\,(n_{i+}\, N)$
Overall accuracy	$\sum_{i=1}^{c} p_{ii}$	$(1\,/N)\sum_{i=1}^{c}(\,n_{ii}N_{i+}/\,n_{i+})$
User's accuracy for *class i*	$p_{ii}\,/\,p_{i+}$	$n_{ii}\,/\,n_{i+}$
Producer's accuracy for class *j*	$p_{jj}\,/\,p_{+j}$	$\frac{n_{jj}\,(N_{j+}/\,n_{j+})}{\sum_{i=1}^{c} n_{ij}\,(\,N_{i+}/\,n_{i+})}$

Where;

i = map class

j = reference class

p_{ij} = proportion of land cover mapped as class i and labeled class j in the reference data

p_{ii} = proportion of correctly mapped points of class i (main diagonal)

p_{i+} = the sum of all p_{ij} values in row i and represents the proportion of area classified as class i

p_{+j} = the sum of all p_{ij} values in column j and represents the proportion of area that is truly class j

n_{ij} = number of sample points in cell (i, j) of the error matrix

n_{i+} = number of sample points in row (land cover class) i of the error matrix

n_{+j} = number of sample points in column (reference class) j of the error matrix

n = number of points in the sample

N_{i+} = number of pixels in the entire region classified (mapped) as class i

N_{+j} = number of pixels in the entire region of reference class j

N = total number of pixels for the entire region

c = number of classes

Table 5. Variance Estimation Formulas for Stratified Random Sampling (Stehman and Foody 2009)

Characteristic	Stratified Random Sampling
Overall accuracy	$\sum_{i=1}^{c} \frac{N_{i+}^2}{N^2} \frac{\hat{U}_i(1-\hat{U}_i)}{n_{i+}-1}$
User's accuracy for map class *i*	$\hat{U}_i\ (1-\hat{U}_i)/(\,n_{i+}-1)$
Producer's accuracy for reference class *j*	$\frac{1}{\hat{N}_{+j}^2}\left[N_{j+}^2\ (1-\hat{P}_j)^2\ \hat{U}_j\ \left(1-\hat{U}_j\right)/\ (n_{j+}-1)+\ \hat{P}_j^2\sum_{i\neq j}^{c} N_{i+}^2\ \frac{n_{ij}}{n_{i+}}\left(1-\frac{n_{ij}}{n_{i+}}\right)/\ (n_{i+}-1)\right]$

where:

$\hat{N}_{+j} = N\ \hat{P}_{+j}$ is the estimated marginal total for reference class *j*

$\hat{U}_i$ = estimated user's accuracy

$\hat{U}_j$ = estimated producer's accuracy

$\hat{P}_j = p_{ii} / p_{+j}$ estimated proportion of area with class *j* in the reference data that is actually mapped as class *j*

3.3.5. Post Classification Change Detection

Annual deforestation rate was calculated for the period between 2000 and 2017. The percent of deforestation and degraded forest expansion was computed using simple mathematical calculations. In addition, the percent of forest gain was also reported. Those procedures were carried out in ArcMap using the area information for each land cover class in the attribute table.

These rates were obtained from the maps in contrast to estimating the rates from the accuracy assessment samples. The two classified land cover maps of 2000 and 2017 were overlaid and the area of gross forest loss (i.e., area that changed from forest to non-forest) and forest gain (i.e. area that changed from non-forest to forest) were computed.

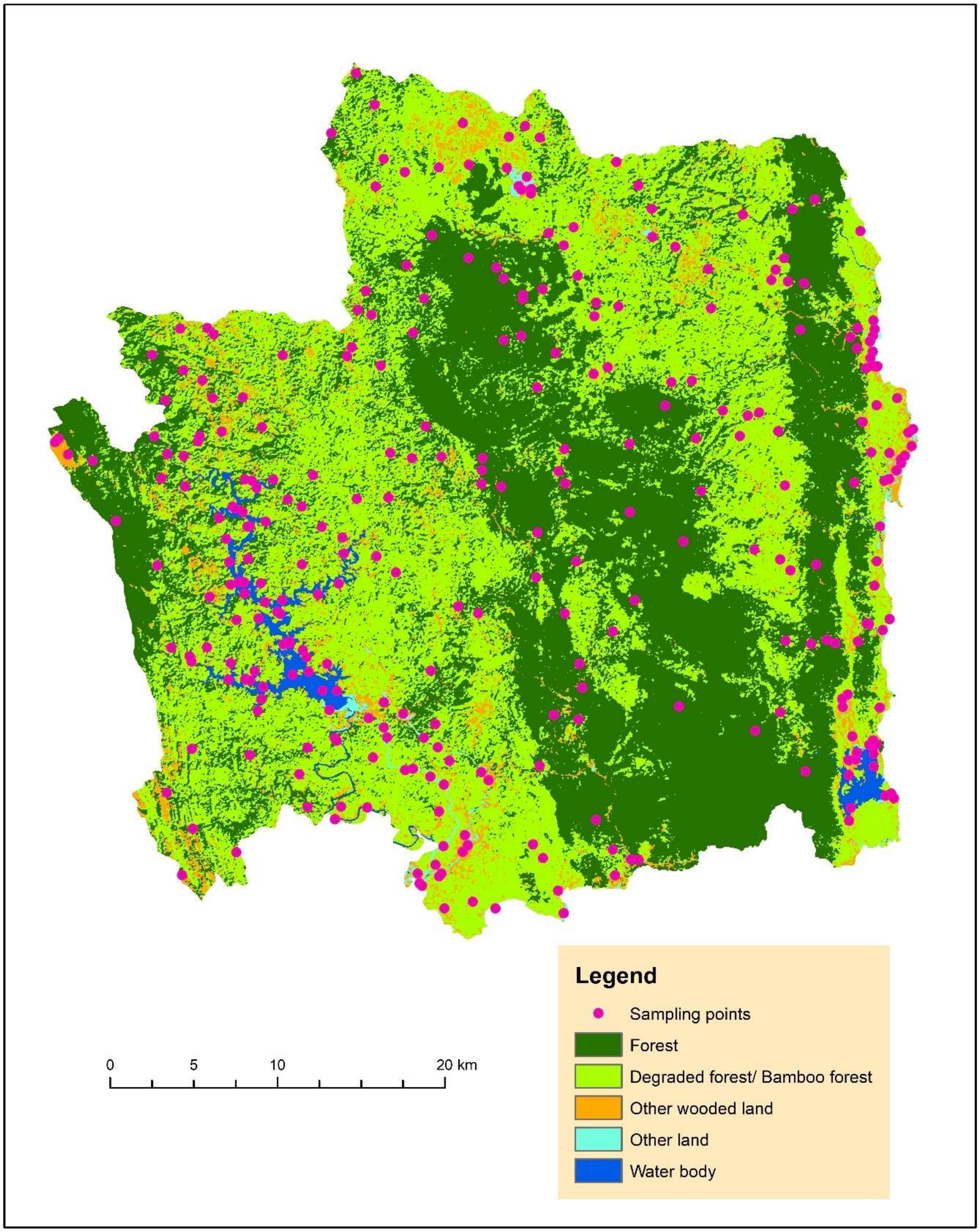


Figure 5. Designation of stratified random points for 2000 land cover map

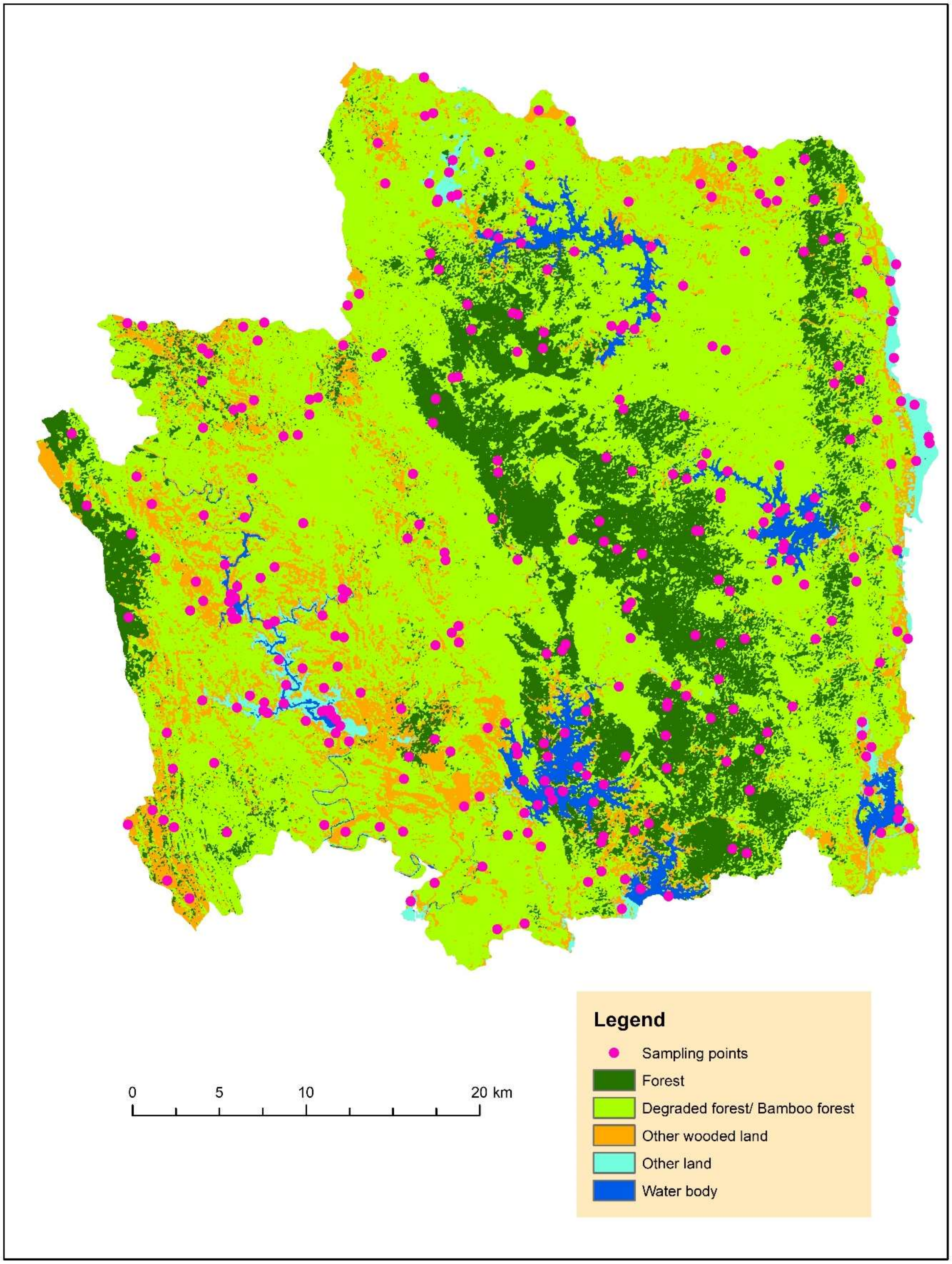


Figure 6. Designation of stratified random points for 2017 land cover map

3.4. GIS Layers and Data Sources

The land cover layer obtained from the supervised classification of 2017 Landsat image is shown in Figure 7.

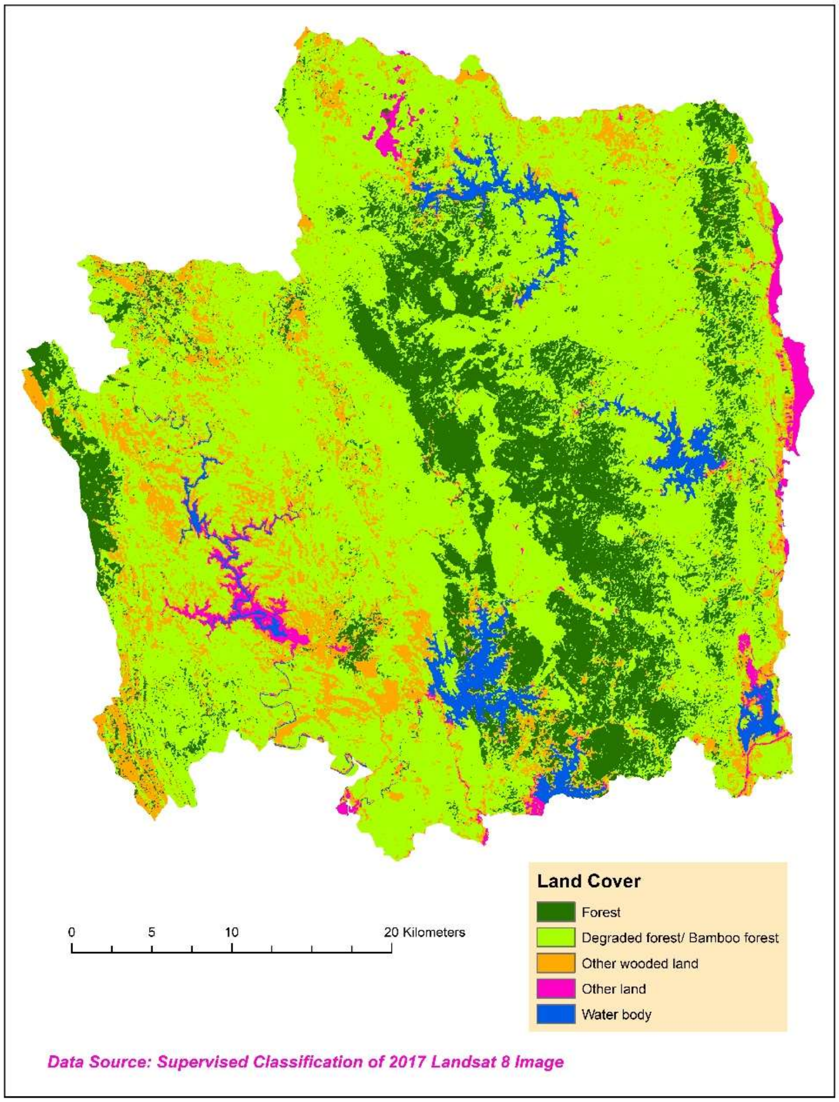


Figure 7. 2017 Land Cover Map

Principally, the study area has temporary logging roads, earth roads, permanent gravel roads (along the boundary line of Baing Dar reserved forest), seasonal forest roads for log transportation, and village and dam access roads. The road (accessibility) layer was obtained from the saved GPS tracking during field inspection coupled with heads-up digitizing from the

Google Earth Pro. As a secondary reference, available road maps of the Forest Department were reviewed while creating the road layer in the ArcMap. Figure 8 shows the accessibility status of the study area. Reserved forests have limited access due to restrictions on public extraction of forest products such as firewood, agricultural use and other activities e.g., camping and fishing (Tun et al. 2016). Because of such kinds of protective rules and regulations, reserved forests usually have constrained accessibility relative to other land.

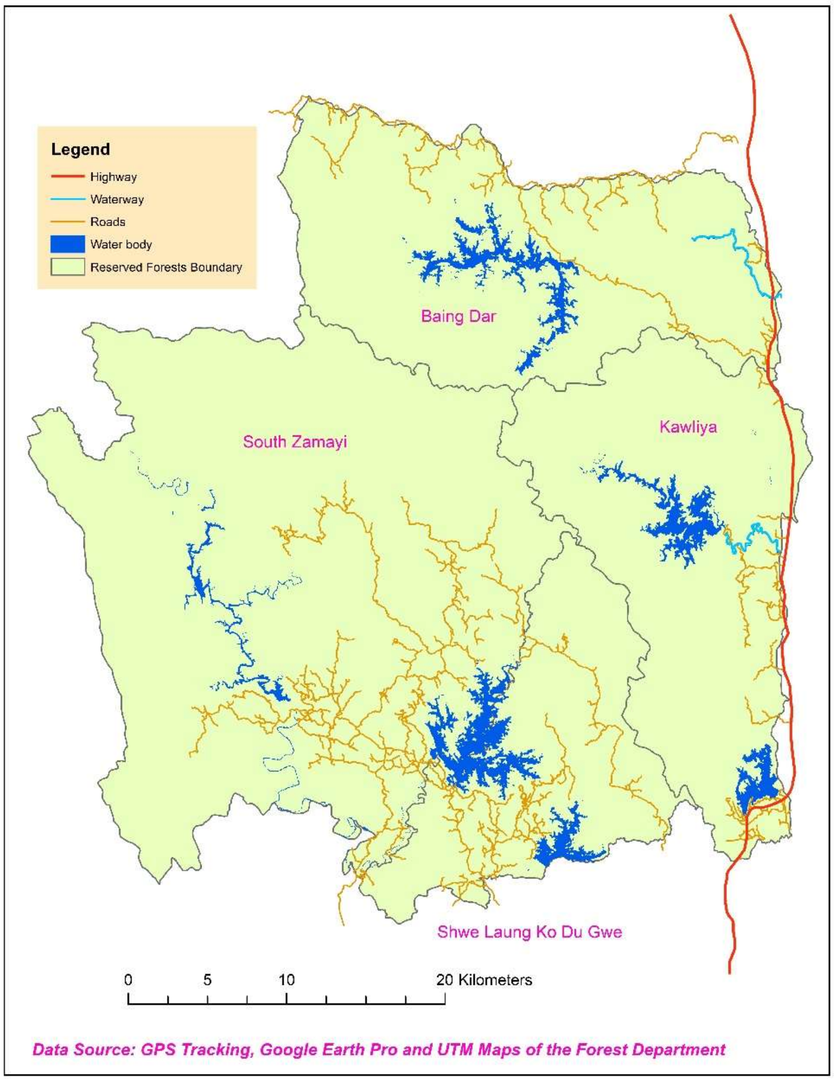


Figure 8. Accessibility of study area. The entire study area is composed of four reserved forests, situated near a highway and thus the forest is somewhat accessible especially along the highway. During the rainy season, accessibility by waterway can possibly be an option.

The slope and aspect were generated in ArcMap from a Digital Elevation Model (DEM), acquired from the USGS website with 30 m pixel size. Figure 9 shows the slope conditions in the study area, which highlight that majority of the study area has slope less than 30%. Figure 10 illustrates the direction of slope (aspect).

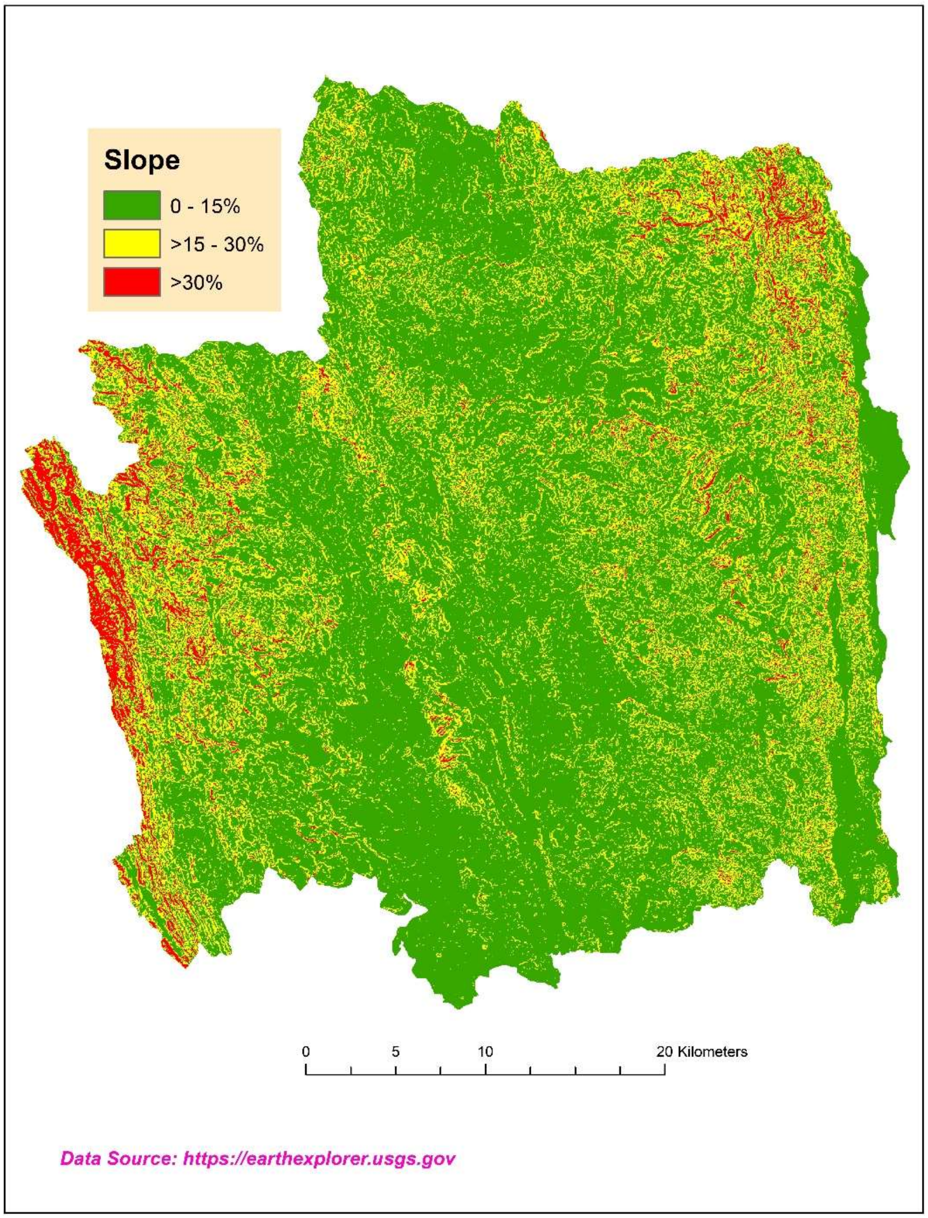


Figure 9. Slope conditions within the study area. Gentle slope predominates. Some areas within South Zamayi reserved forest are steeper and consequently, have limited accessibility.

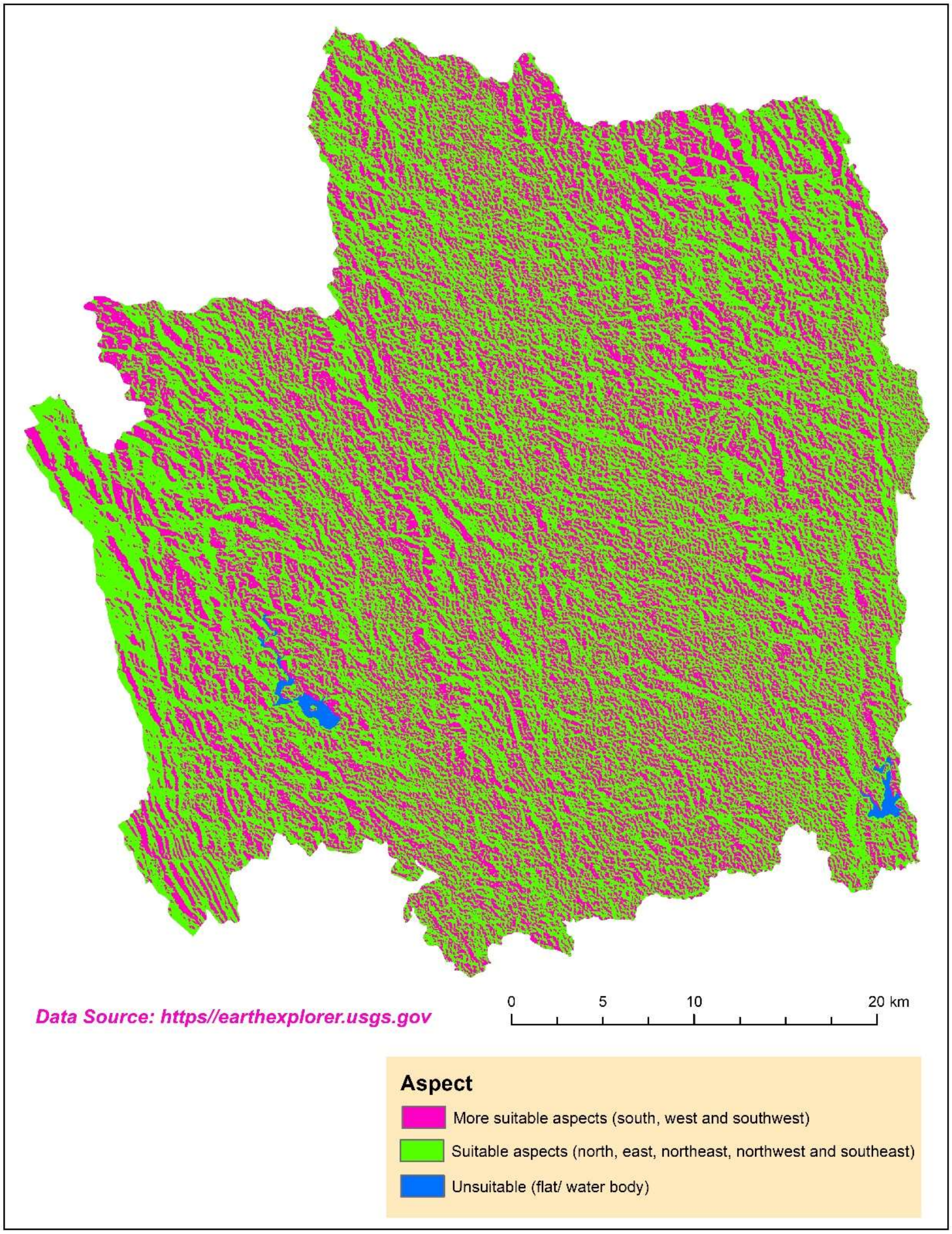


Figure 10. Aspect (slope faces) within study area. Flat areas (with the value of -1) are water body and thus, are placed under unsuitable category. Aspects having more sunlight exposure are determined as more suitable areas and other aspects are put under suitable areas category.

Frequency of teak logging between 2010 and 2014 was considered while locating candidate sites for assisted natural regeneration. According to the Forest Department's records, 2014 was the final year for commercial teak extraction in the study area. A nationwide logging ban went into effect in 2016. Logging records such as reserved forests, compartment numbers, area, logging times, year of extraction and number of trees cut were obtained from the Bago District, Forest Department. A logging intensity layer was generated (Figure 11) from information about activities such as no logging, one-time logging and two-time logging during the teak logging operation that occurred between 2010 and 2014.

Community Forestry Instructions (2016) defines community forestry as forestry operations in which local people themselves participate in forest management activities. Its operations consist of setting up of new plantations and managing forests to generate local employment and income opportunities that can fulfill from subsistence to commercial scale; sustain environmental conditions and supply food production. After intimate discussion with the foresters, Dawe was selected as the community forestry village in this study. The selected village is located in South Zamayi reserved forest. Proximity to the village was considered as one of the data layers for community forestry. The village location was marked with GPS during field work (Figure 12). The Euclidean distance tool was employed to reclassify the distance ranges from the village.

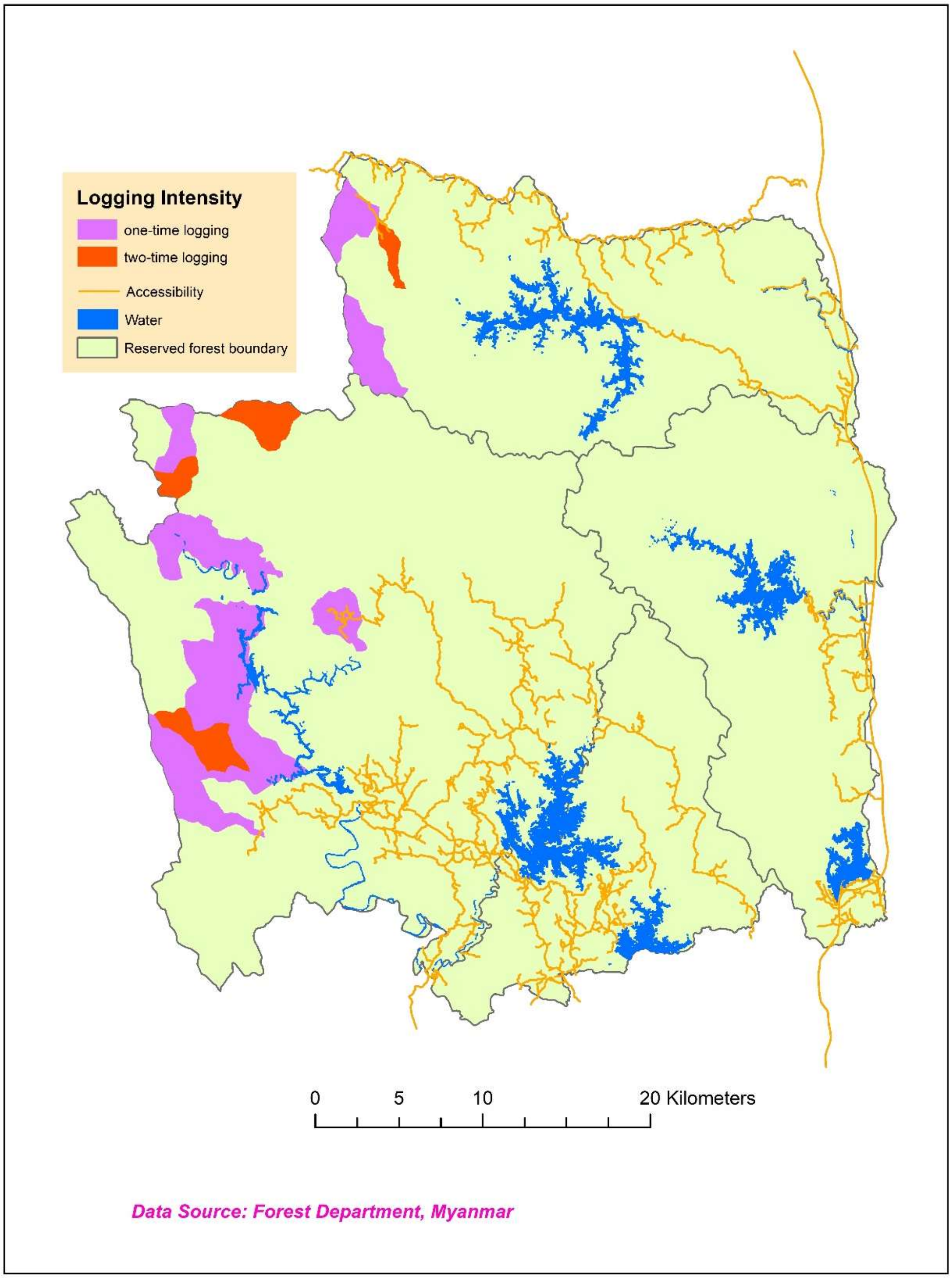


Figure 11. Teak harvested areas from 2000 to 2014. No logging means areas with no teak logging between 2010 and 2014. Teak extraction might occur in most parts of the study area in the past but the most previous five-year logging records were considered for the sake of immediate actions in this study.

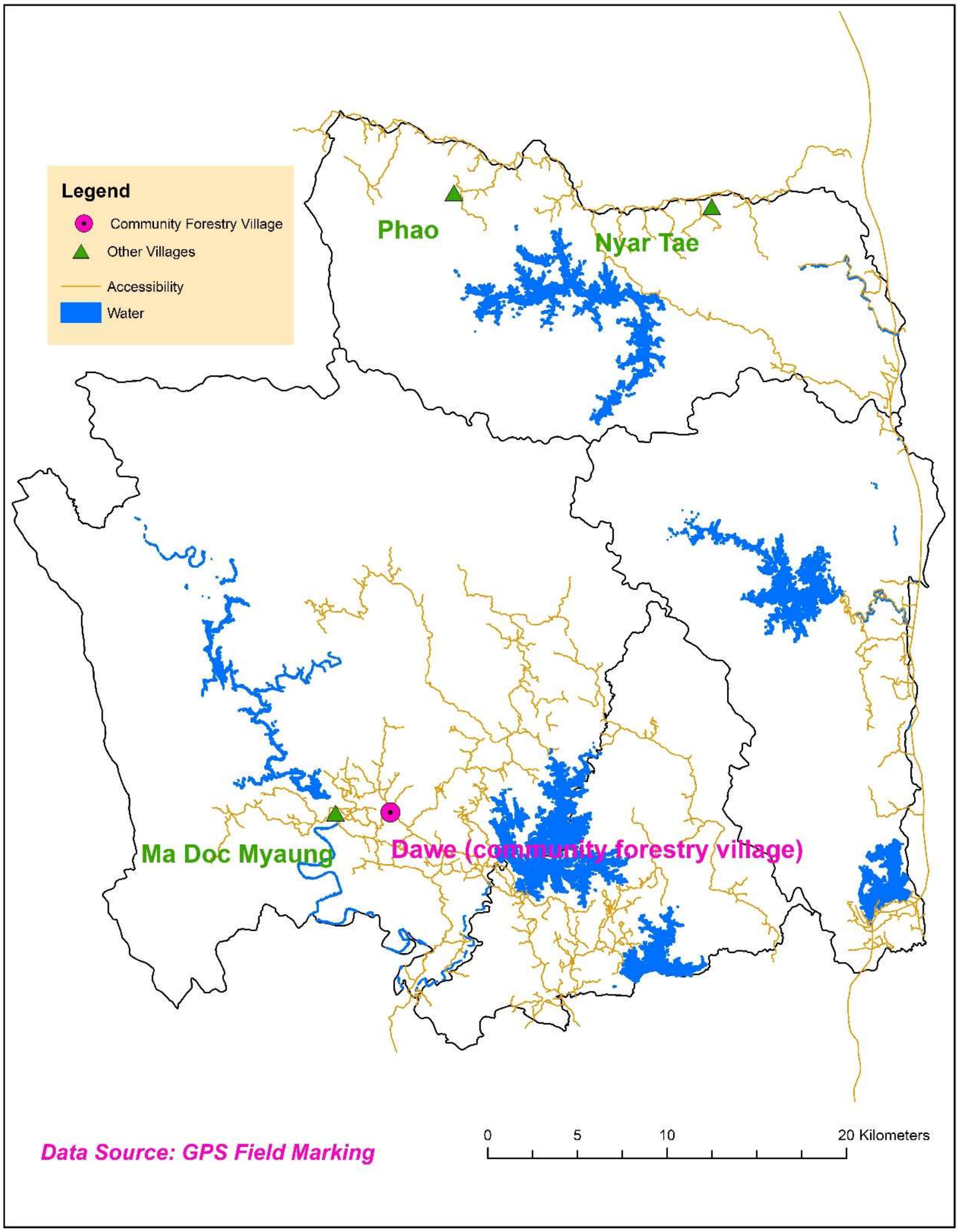


Figure 12. Location of community forestry village and its road access. In addition to the selected community forestry village (i.e., Dawe), there are three other villages, namely Ma Doc Myaung, Phao and Nyar Tae, in the study area. Those villages have been given the right to manage their own community forestry.

3.5. GIS-assisted Multi-criteria Analysis for Determining Potential Teak Plantation Sites

Deforestation and forest degradation has been threatening the sustainability of quality forested conditions in the study area. Artificial regeneration in terms of teak plantation establishment is a means to improve the teak composition and to try to remedy the decline in forest cover. The Forest Department's criteria for plantation establishment were used to assess suitable sites. In addition, the literature on teak ecology was reviewed to better understand the environmental requirements of teak. Furthermore, feedback from Forest Department foresters with considerable experience with plantation establishment and maintenance was gathered. Given that plantation establishment operations are ideally carried out during the rainy season, their professional input on how far they could reach from the roads was a key factor from a practical standpoint. This qualitative input coupled with a literature review resulted in the plantation establishment criteria (Table 6).

Table 6. Location selection criteria for teak plantations establishment

Criteria	Value	Rank	Weight
Land Cover	Other Wooded Land	2	40%
	Degraded Forest (Bamboo Forest)	1	
	Other Land Cover Classes (Forest, Other Land and Water)	0	
Distance to Roads	0-0.5 mile (800 m)	2	30%
	>0.5 mile (800 m)- 1 mile (1,600 m)	1	
	> 1 mile (1,600 m)	0	
Slope	0-15%	2	20%
	>15%-30%	1	
	>30%	0	
Aspect	South, West and Southwest	2	10%
	North, East, Southeast, Northeast and Northwest	1	
	Flat (i.e., water body)	0	

3.5.1. Working Circles and Potential Teak Plantation Sites

The Forest Department divides the reserved forests into management units (referred to as working circles in Myanmar). Management units or working circles are areas divided within the reserved forests based on the specific forest management objectives (Table 7). Ideally, the Forest Department implements reforestation activities in accordance with the objectives associated with that management unit. Generally, there are seven working circles: production, plantation, watershed, local supply, non-wood forest products, protected areas, and areas that are not included in the working circles (Bago District Working Plan 2016). According to the Bago District Working Plan (2016), a particular working circle may support more than one management objective e.g., non-wood forest products working circle is integrated into the production working circle.

The study area consists of a negligible percentage of areas that are not included in the working circles, and there is no protected area (Table 8). Working circles for production, plantation, watershed, local supply and non-wood forest products are found in the study area (Figure 13). Ideally, plantation, watershed and local supply working circles are recommended for plantation establishment. The non-wood forest products working circle is aimed for supplying forest products (e.g., bamboo) other than timber, and in some cases, the non-wood forest products working circle is integrated into the production working circle (Table 8). But the proportion of the non-wood forest products working circle was also very low in this study area and thus, those small areas were not excluded while considering plantation areas. Thus, the only problem working circle for proposing plantation sites was the production working circle. Due to the extended 10-year logging ban in the study area, the production working circle, which was originally intended only for logging, would not function as it defined. Therefore, even though areas within the production working circle were not fundamentally selected for plantations according to working circle objectives of the Forest Department, this study considered the production working circle for candidate plantation sites as well. Thus, any sites falling within the study area were given equal probability of being selected for teak plantations during GIS site suitability analyses.

Table 7. Objectives of respective working circles. Community forestry can be proposed in any other working circles.

No.	Working Circles	Objective
1	Production	For logging
2	Plantation	For private and Forest Department plantation establishment (teak and other commercial hardwood)
3	Watershed	For the conservation of watershed areas
4	Local Supply/ Community Forestry	For local supply and community forestry establishment
5	Non-wood forest products	For non-wood forest products e.g., bamboos
6	Protected Areas	For protection purposes e.g., elephant conservation areas, Ramsar Sites (i.e., wetland conservation areas)
7	Areas not included in the working circles	e.g., high-way roads, encroached settlements

Table 8. Composition of working circles in each reserved forest (Source: Bago district working plan 2016)

Reserved Forest	Area (ha)	Composition of Working Circles	Remark
South-Zamari	38,669	1) Production (59%) 2) Plantation (8 %) 3) Local Supply (0.03%) 4) Watershed (33%) 5) Areas not included in working circles (0.03%)	Non-wood forest products working circle is integrated into the production working circle.
Shwe Laung Ko Du Gwe	35,761	1) Production (51%) 2) Plantation (34%) 3) Watershed (14%)	Non-wood forest products working circle is integrated into

Reserved Forest	Area (ha)	Composition of Working Circles	Remark
			the production working circle.
Baing Dar	21,827	1) Plantation (37%) 2) Local supply (0.004%) 3) Watershed (63%)	
Kawliya	79,710	1) Plantation (34%) 2) Local supply/CF (2%) 3) Watershed (57%) 4) Non-wood Forest Products (7%)	

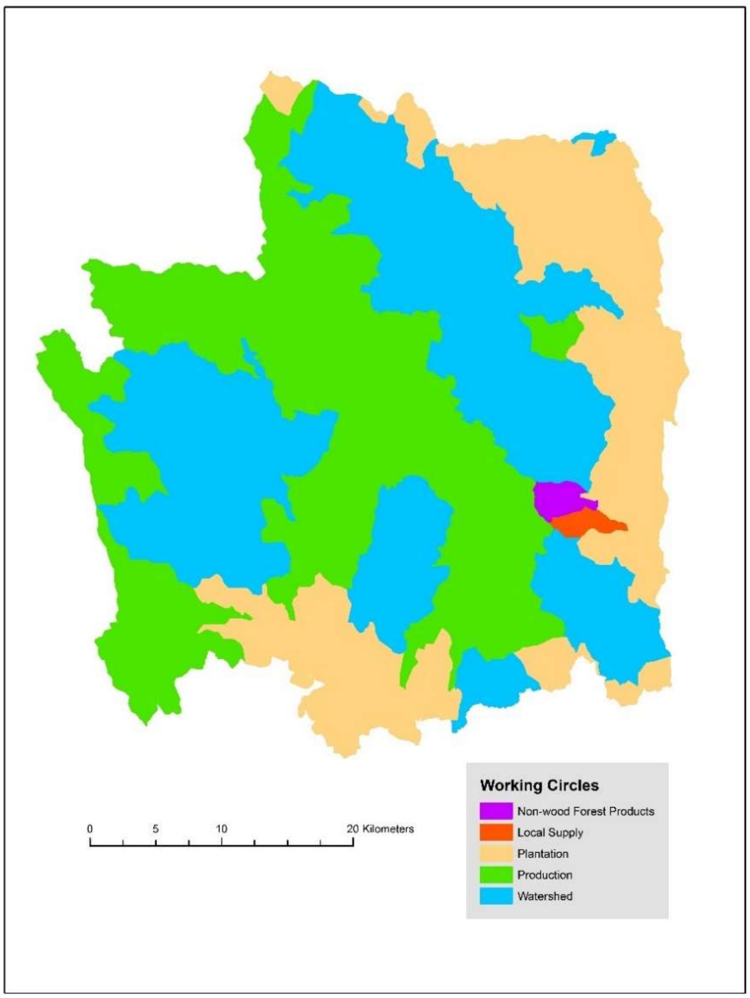


Figure 13. Map showing the division of working circles in the study area (Source: Bago district working plan 2016)

3.5.2. Location Selection Criteria for Teak Plantations Establishment

Land cover was considered as the most important criterion (40% weight) for locating potential sites for teak plantations. Areas of degraded forest/bamboo forest as well as other wooded land (including scrubland, shifting cultivation, literally non-forest areas) should be targeted for plantation establishment. Thus, other wooded land was ranked as the first priority and degraded forests/ bamboo forests were considered as second priority for plantation establishment. Other land cover classes such as forest, other land (including roads, agriculture, open/bare soil, settlements, roads, and infrastructure) and water were ranked as unsuitable areas for plantation establishment.

Because accessibility influences the cost and success of long-term plantation management, proximity to roads was ranked as the second most important criterion (30%). Based on the opinions of local Forest Department foresters, 0-800 m was the most appropriate condition to have regular access to the plantation site. The range of > 800m - 1600 m was set up as the second-best condition. Beyond that point (1,600 m), it was ranked as unsuitable. It was found that 55% of the study area was eliminated by this criterion (i.e., beyond 1,600 m). To categorize the distance classes from the road, the Euclidean distance (Spatial Analyst) tool available in ArcMap was used. The Euclidean distance can give the distance from each cell in the raster to the closest source (ESRI, 2016). In this case, roads were the sources to categorize the distance ranges.

Setting up criteria and ranking for slopes relied on the published literature (Aguirre-Salado et al. 2015; Muñoz-Flores et al. 2017). Slopes from 0 to 15% were regarded as suitable for artificial regeneration. Slopes from 15 to 30% were ranked second and slopes exceeding 30% were not considered. As teak is a shade intolerant species, sites having more sunlight (south, west and southwest aspect) were considered as ideal conditions. Other aspects were taken into account but with a lower rank.

The weights for the respective criteria were decided by checking the results derived from a number of sensitivity analyses. Having prior knowledge about some of the suitable sites for teak plantations was key to saving time when conducting repeated analyses. If the results of a trial analysis overlapped with known suitable sites, the percent weights assigned to that spatial analysis was selected.

3.5.3. Flexible GIS Model

The GIS model builder is an effective way to do editing and sensitivity analysis. Thus, a GIS model was developed to conduct spatial analysis. Essentially, two GIS models were developed: flexible GIS model and rigid GIS model. In this flexible GIS model (Figure 14), weighted assignments to each criterion were considered. The weight allotted to each GIS layer was described in the GIS model (Figure 14). The weighted overlay tool available in ArcMap was not used due to its default rounding function. To address such rounded integer values, it can be possible to extend the scale of input rasters if the weighted overlay tool is preferred. Instead, a raster calculator tool was consistently employed to maintain more precise continuous values in this study. For the reclassifications that are next to each criterion (Figure 14), the rankings defined in Table 6 were used (i.e., ranks of 0, 1 and 2). The function of the raster calculator was the addition of the multiplications among reclassified values (0, 1 and 2) and weights (i.e., 40% for land cover, 30% for accessibility, 20% for slope and 10% for aspect) of respective criteria.

The resultant weighted overlay output ranged from 0 to 2. Reclassification was again conducted in order to provide sites with suitability indices. In terms of suitability classes, the value 0 was classified as unsuitable, the value ranging from > 0 to 0.5 as low, from > 0.5 to 1.0 as medium, from > 1.0 to 1.5 as high and from > 1.5 to 2.0 as very high (Table 9).

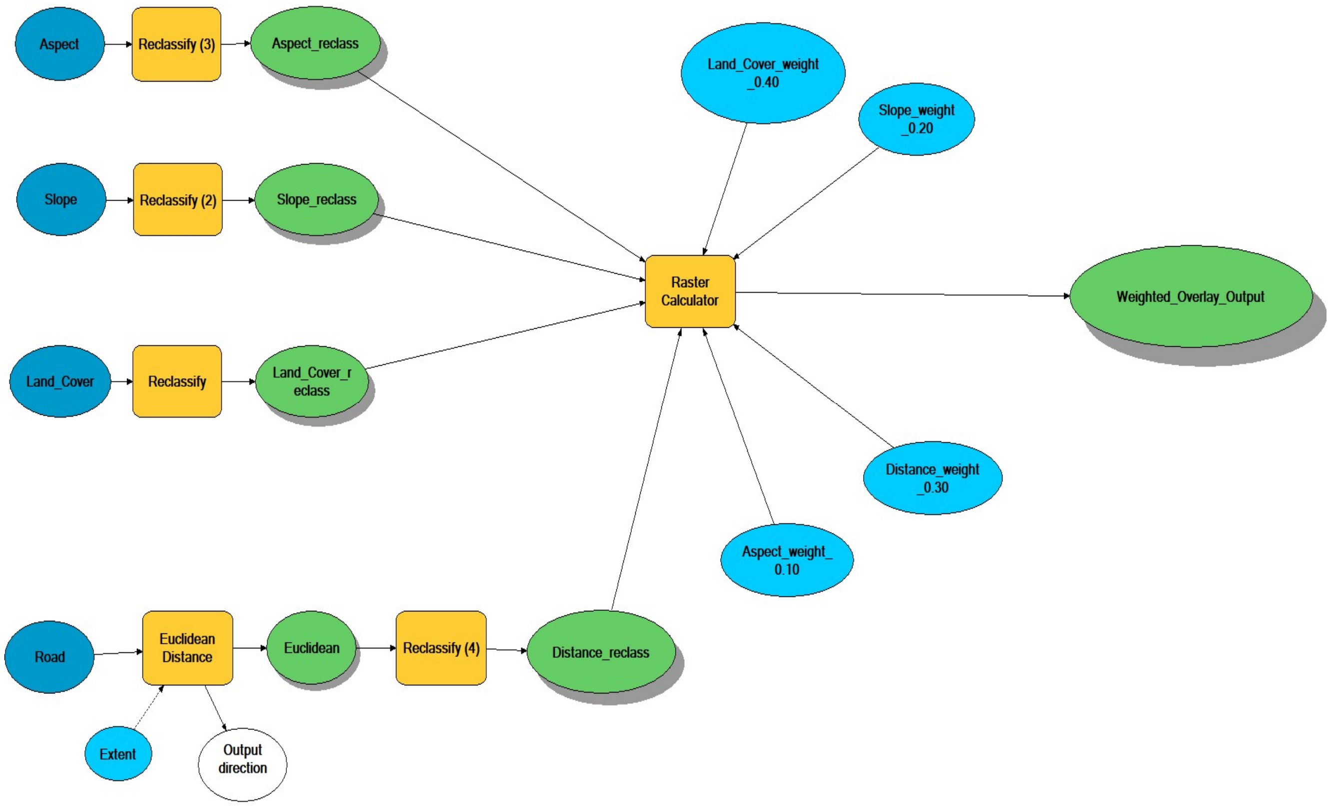


Figure 14. Flexible GIS model for locating optimal teak plantation areas. The weighted overlay approach was applied to obtain the results. The output values ranged from 0 to 2 with continuous (decimal) values in-between.

Table 9. Defining site suitability classes for flexible GIS model

Value Range	Suitability Class
0	Unsuitable
> 0-0.5	Low
> 0.5-1	Medium
> 1-1.5	High
> 1.5-2	Very High

3.5.4. Rigid GIS Model

The rigid GIS model is the combination of weighted overlay (flexible GIS model) and non-weighted overlay outputs. Recall that the flexible GIS model considered weight for each GIS layer during analysis and the resultant values ranged from 0 to 2 with continuous (decimal) values in-between (Figure 14). The output of weighted overlay was integrated into this rigid GIS model. The initial analyses of the rigid model did not consider weight. Thus, multiplying four data layers (each layer was reclassified as 0, 1 and 2) using the raster calculator gave the values of 0, 1, 2, 4, 8 and 16. To eliminate unsuitable areas (i.e., sites having 0 value), using reclassify tool, the values of the non-weighted overlay were reclassified again: 0 as 0 and the other values (i.e., 1, 2, 4, 8 and 16) as 1.Then, multiplying those two outputs, reclassified weighted output (continuous values ranging from 0 to 2) and reclassified non-weighted output (0 and 1), gave the continuous values ranging between 0 and 2 (Figure 15).

Afterwards, another reclassification was done to present candidate land areas with suitability classes. In terms of suitability ranking, sites with value 0 were designated as unsuitable while sites having values > 0 and 1.3 as low suitability, >1.3 and 1.6 as medium suitability, >1.6 and 1.9 as high suitability and >1.9 as very high suitability (Table 10).

The plantation size was limited between 40 ha (approximately 100 acres) and 200 ha (approximately 500 acres). To obtain the required size range, it was screened outside the model builder. The model resulted in sites with raster format. Such raster results were converted into vector using the “raster to polygon” tool. Thereafter, in the attribute table, the “select by attributes” tool was used to obtain the polygons that had the desirable area range (i.e., between 40 ha and 200 ha).

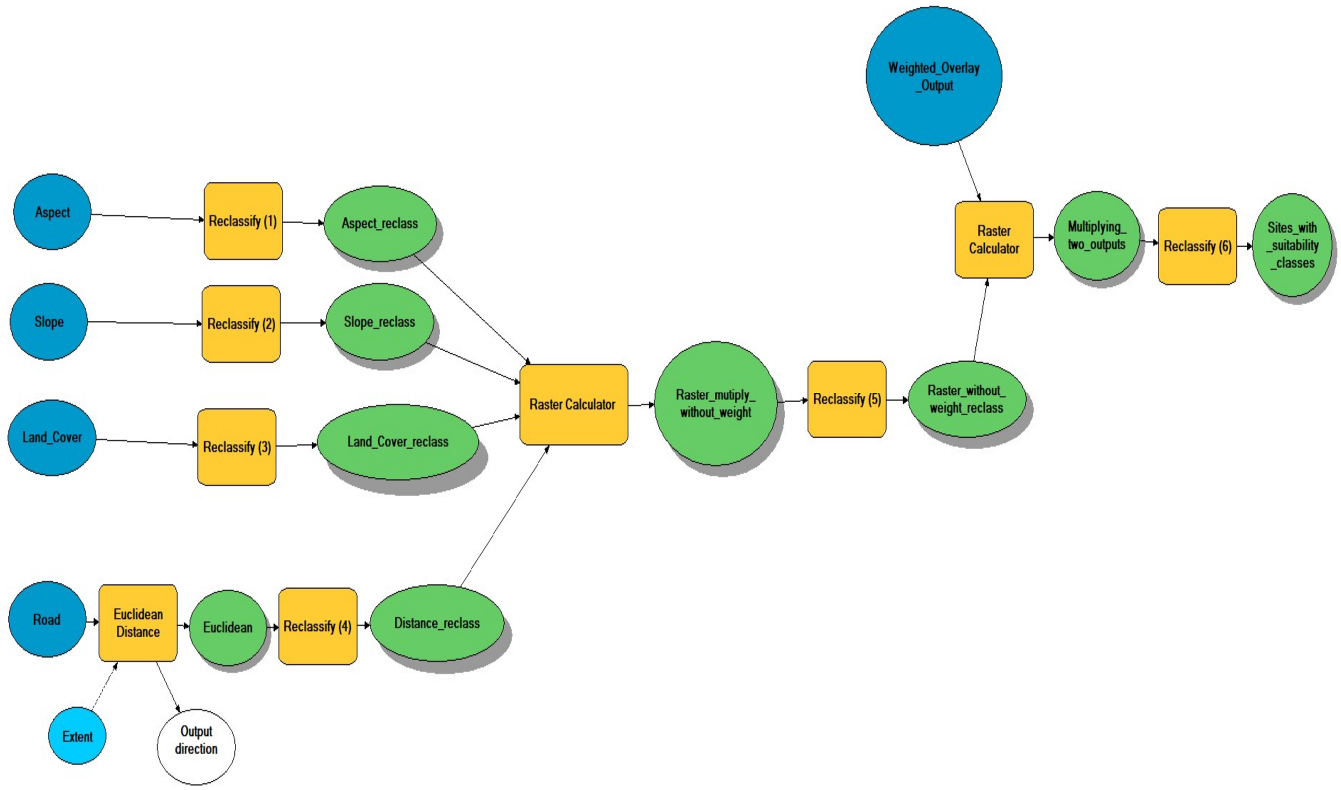


Figure 15. Rigid GIS model for locating optimal teak plantation areas. The final output values range from 0 to 2 with continuous (decimal) values in-between. It integrated weighted overlay and non-weighted overlay.

Table 10. Defining site suitability classes for rigid GIS model

Value Range	Suitability Class
0	Unsuitable
>0-1.3	Low
>1.3-1.6	Medium
>1.6-1.9	High
>1.9-2	Very High

3.5.5. Overlay of the Rigid GIS Model on the Flexible GIS Model

The rigid GIS-suggested sites were overlaid on top of the flexible GIS-suggested sites to investigate whether the results of the rigid model fall only in the most suitable plantation zones recommended by the flexible model.

3.5.6. Verifying the GIS-suggested Teak Plantation Sites with Local Foresters

Due to access issues related to the wet season, field-based ground validation was not possible. Consequently, performance assessment of the GIS models was conducted by visiting field stations and interviewing local foresters. Office data from the corresponding Forest Department Township were reviewed for secondary confirmation. Five local field-based foresters and two office database staff were involved in assessing the models.

For better display, the 24-inch and larger vinyl maps were printed out and used while interviewing. The reasonably large vinyl maps included reserved forests and township boundaries with compartment layers underneath (Figure 16). Each GIS-recommended plantation site was labelled with serial numbers on the map so that local foresters could readily identify the locations together with its respective land cover, land use and pertinent background information.

The resulting GIS-recommended sites were categorized into “already planted”, “planted but need to be restored” and “not yet planted” based on the existing land use conditions, accessed from the Forest Department. Thereafter, the “already planted” sites were eliminated. Then the other available two categories, “planted but need to be restored” and “not yet planted”, were ranked into low, medium, high and very high, based on land suitability indices. This ranking was based on subjective criteria by the local foresters. If there were areas considered as inappropriate by local foresters, those sites were classified as unsuitable.

Figure 16. Vinyl maps used in navigating the GIS-suggested sites

3.6. GIS-assisted Multi-criteria Analysis for Determining Potential Assisted Natural Regeneration Sites

To generate ideas about locating possible areas for the implementation of assisted natural regeneration, consultations with the Forest Department officials and field-based foresters were conducted at the beginning of the process. Ideally, the guided operations for assisted natural regeneration involve improvement felling, thinning, pruning, climber cutting (removing or cutting climbers that disturb the main tree species), coppicing, weeding, dispersing seeds and fire protection (Standard Operating Procedures 2016).

The Standard Operating Procedures (SOP) from the Forest Department of Myanmar for promoting natural regeneration contributed to the development of criteria. A thorough literature review further improved the development of required criteria for locating the most optimal sites for natural regeneration.

3.6.1. Location Selection Criteria for Assisted Natural Regeneration

Similar to the steps employed in determination of teak plantation sites, criteria were developed to obtain suitable areas for assisted natural regeneration (Table 11). In terms of size, 20 ha (approximately 50 acres) was considered as the minimum threshold for this operation. The natural regeneration is not as costly as teak plantations. Moreover, accessibility is not as challenging as is the case with teak plantations, because it is usually conducted during the winter (dry) season. Thus, the maximum area for assisted natural regeneration was not specified. Like plantations, the size criterion was fulfilled singly outside the model builder.

Previously harvested areas during 2010-2014, particularly for teak, were considered as suitable areas for assisted natural regeneration. In this spatial analysis, logging intensity was considered for ranking the priority. Sites with the most intense logging during the past 5 years were weighted highest. Thus, the areas harvested twice were ranked 2 (more suitable) while areas harvested once were ranked 1 (suitable), and those areas with no harvesting during the past five years were not considered for assisted natural regeneration (rank 0). Consequently, any site with harvesting completed more than 5 years ago would not be a candidate for assisted natural regeneration. Given that timber harvesting is the key factor in suggesting natural regeneration, logging intensity was the most heavily weighted input (30%) in this GIS model.

The criterion with the second highest weight is land cover status (25% of total weight). Recall that non-forest areas and degraded forests/ bamboo forests were regarded as suitable areas for extensive plantation establishment, and forests after logging were considered as most suitable (thus ranked as 2) for natural regeneration. The second priority, with a ranking of 1, was assigned to degraded (bamboo) forest areas. Other land cover types (other wooded land, other land and water body) were not recommended as suitable sites and thus ranked as 0.

The third most important criterion was slope, allotted a weight of 20%. As stated earlier, the seasonal and working conditions for natural regeneration (during winter season) were much more favorable than plantation establishment (during rainy season). Steeper areas are quite challenging for artificial regeneration (like plantation establishment). In that case, natural regeneration is the only viable option. However, if it is too steep, it will be tough for field work, resulting in the lowest score. In the GIS-based planning for forestry and conservation activities study, Webb and Thiha (2002) categorized six slope classes: moderately sloping (< 8%), sloping (8% - 27%), strongly sloping (27% - 36%), very strongly sloping (36% - 47%), steep (47% - 58%) and very steep (> 58%). This classification system was based on biophysical standpoints. In this study, the sites with the highest priority (ranked 2) had slopes averaging between 0-20%. The second priority (rank 1) went to sites with slopes averaging between 20% and 40%. Areas with slopes higher than 40% were considered unsuitable (rank 0).

Accessibility was given a weight of 15%. The entire study area is composed of four reserved forests that are situated near highways (particularly Kawliya and Baing Dar) and thus somewhat accessible. Additionally, during the rainy season, access via waterways can sometimes be an option. Two types of forest roads, forest access and feeder, are mainly observed at logging sites, and those roads can be accessed only in the dry season (Khai et al. 2016). Myanmar Selection System (MSS) mentions that logging roads should be de-commissioned after harvesting operations to limit accessibility, which aims to curb illegal logging (Khai et al. 2016). According to interviews, it is possible to set the walking distance up to approximately 5 km (3 miles) in a day. Thus, 0-5 km (3 miles) was set as the most optimal range (i.e., rank 2). Sites which are between 3 and 8 miles from a road were ranked 1, while sites over 8 miles were assigned a rank of 0. In addition to interviewing the local Forest Department foresters, sensitivity analysis in the GIS model was repeatedly done to find the best distance range. The sensitivity analysis proved that a distance range of 8 miles was sufficient to cover the study areas to implement assisted natural regeneration. Practically, it is challenging to reach the sites that are beyond 8 miles even though weather conditions may not constrain the accessibility.

Aspect was considered with a weight of 10%. Sites with more sunlight such as south, west and southwest were ranked as 2. The other aspects with limited light were ranked as 1.

Table 11. Location selection criteria for assisted natural regeneration

Criteria	Value	Rank	Weight
Logging Intensity	2 times	2	30%
	1 time	1	
	No Logging	0	
Land Cover	Forest	2	25%
	Degraded Forest (Bamboo Forest) and Other Wooded Land	1	
	Other Land Cover Classes (Other and Water)	0	
Slope	0-20%	2	20%
	>20%-40%	1	
	>40%	0	
Distance to Roads	0-3 miles (5 km)	2	15%
	>3 miles (5 km)- 8 miles (13 m)	1	
	>8 miles (12,874 m)	0	
Aspect	South, West and Southwest	2	10%
	North, East, Southeast, Northeast and Northwest	1	
	Flat (water body)	0	

3.6.2. GIS Model

Like the plantation model, overlay analysis was also employed in this study. Two steps were used to generate the final results. The steps in the GIS model were developed was the same as the rigid model for teak plantations. The first model (Figure 17) assigned weights to each GIS layer (Table 11). The function of the raster calculator is multiplying the reclassified values (0, 1 and 2) for individual criteria with the weights for the respective criteria (i.e., 30% for logging intensity, 25% for land cover, 20% for slope, 15% for distance to roads and 10% for aspect).

The second model multiplied the output of the first model (i.e., weighted overlay output with continuous values ranging from 0 to 2) by the output of a non-weighted-overlay (0 and 1 after reclassification) as shown in Figure 18. The resultant values for both models were reclassified to obtain the site suitability indices. In terms of land suitability indices, sites with value 0 were defined as unsuitable, values between > 0 and 1.3 were low, between > 1.3 and 1.6 as medium and between > 1.6 and 2 as high (Table 12).

The minimum operation size was considered as 20 ha (approximately 50 acres). There was no upper size limit specified for assisted natural regeneration. To obtain the minimum size requirements, it was separately carried out outside the GIS model. The resultant rasters from the model were converted into polygons. Then, the minimum size (i.e., 20 ha) and above was obtained using the “select by attributes” tool. That step could be readily accomplished in the attribute table.

Table 12. Defining site suitability classes for assisted natural regeneration

Value Range	Suitability Class
0	Unsuitable
>0 -1.3	Low
>1.3-1.6	Medium
>1.6-2	High

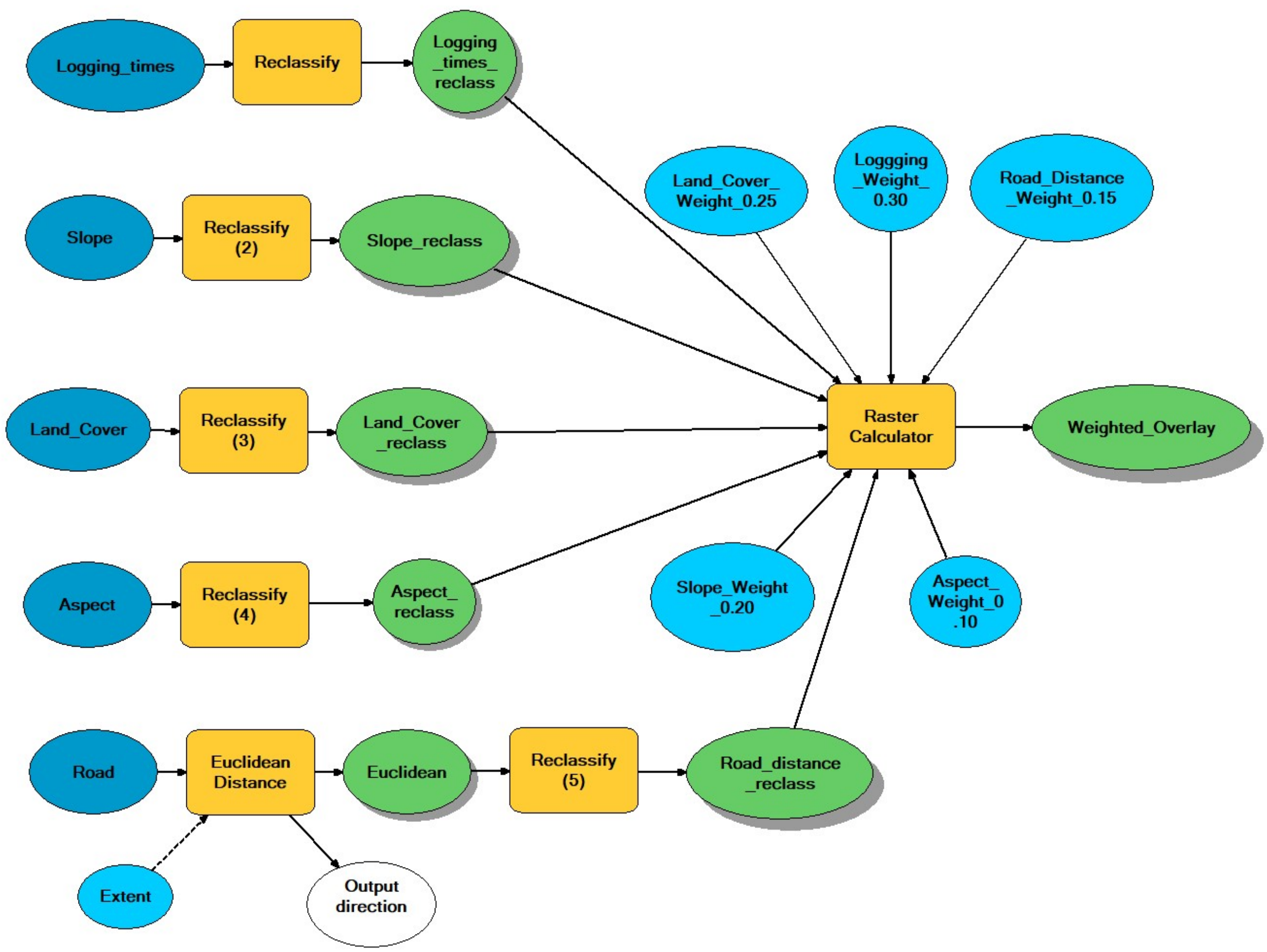


Figure 17. Weighted overlay model for assisted natural regeneration. The output values ranged from 0 to 2 with continuous (decimal) values in-between.

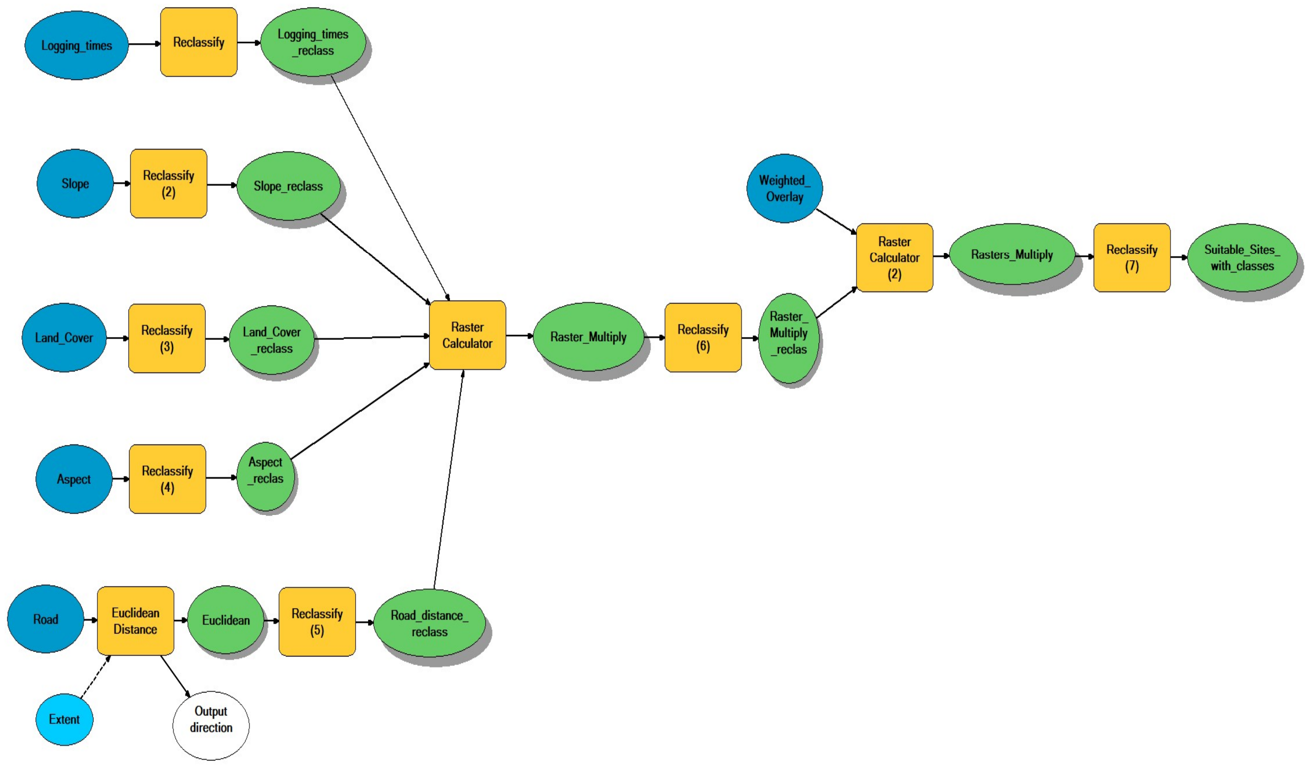


Figure 18. Final model, which integrates weighted overlay and non-weighted overlay outputs to obtain the end results (i.e., decimal values ranging between 0 and 2).

3.6.3. Verifying the GIS-suggested Assisted Natural Regeneration Sites with Local Foresters

Interviews with the responsible field-based Forest Department's personnel were performed to assess the reliability of the employed GIS model. Using available office data, especially existing land use data and large legible 24-inch vinyl maps, allowed the foresters to evaluate the degree of applicability of the GIS model (Figure 19).

Figure 19. Sizable Bago District map displayed at the Forest Department's office

3.7. GIS-assisted Multi-criteria Analysis for Determining Potential Community Forestry Sites

Assisted natural regeneration is mainly conducted by the Forest Department in the reserved forests. Other than the Forest Department, local people who received a community forestry certificate are given the rights to establish new plantations and forest management activities including assisted natural regeneration only within the community forests. Assisted natural regeneration is the responsibility of the Forest Department because all reserved forests are the property of the government and there is no private forest in Myanmar. There are commercial private plantations (but not private forestry) with a 30-year land lease agreement in the reserved forests of the study area. Consequently, the Forest Department, private companies and individuals are putting forth their efforts in reforestation activities in the study area. In addition, there are feasible options to support the participation of community forestry in teak restoration strategies. As per Community Forestry Instructions (2016), the local community can get involved in establishing new plantations to provide employment and income alternatives from need-based to commercial level by obtaining a community forestry certificate from the Forest Department.

Officially issued in 2016, the Community Forestry Instructions – CFI 2016, customized the former CFI 1995, was a good reference for setting up the criteria for community forestry suitable sites. Available published papers and relevant literature were reviewed for justifications.

3.7.1. Location Selection Criteria for Community Forestry

Community forestry is aimed for reforestation with the involvement of local people, and it is a means of encouraging people participation. From a management perspective, the minimum size was specified as 20 ha (about 50 acres) although this size limit was not formally set up in departmental instructions. The reason for setting the minimum size as 20 ha was that in addition to larger areas, small community forestry areas (i.e., less than 20 ha) would also be possible to propose within the 20-ha area. In addition to the size specification, 5 criteria were considered for this spatial analysis (Table 13).

Non-forest areas and degraded forests were considered as target areas for community forestry. Land cover was assigned as the most important criterion (30% of total weight) in this analysis. In this land cover classification, other wooded land was defined as non-forest areas such as scrubland, young plantations and shifting cultivation. According to field observations and land cover classification perspectives, young plantations have exposed soil due to prior slash-and-burn site preparation with some underlying vegetation cover. Those situations were not qualified for putting under degraded forest/ bamboo forest land cover type, and thus young plantations were considered as other wooded land. Thus, the suitability score of other wooded land was ranked as 2. Degraded forests/ bamboo forests were defined with a suitability rank of 1. Other land cover types were designated as suitability rank 0.

Another consideration was slope (25% weight). A review of the literature was conducted to determine the appropriate slope requirements for community forestry. Webb and Thiha (2002) categorized six slope classes: moderately sloping (< 8%), sloping (8% - 27%), strongly sloping (27% - 36%), very strongly sloping (36% - 47%), steep (47% - 58%) and very steep (> 58%). The GIS-based agroforestry suitability analysis of Ahmad et al. (2017) ranked the sites having slopes with less than 4 degrees as the high suitable areas, between 4 degrees (7%) and 9 degrees (16%) as medium suitable areas, and greater than 9 degrees (16%) as low suitable areas. In the study area, the taungya method is principally used for the establishment of teak plantations, and it involves the application of agroforestry practices. Furthermore, a community forestry user group can practice a variety of achievable agroforestry methods which are compatible with local conditions (Community Forestry Instructions 2016). User group refers to active forest dependent households living in the village for at least 5 consecutive years and who are interested in forestry activities within a perimeter of 5 miles from their village (Community Forestry Instructions 2016). Thus, in this case, agroforestry-suited biophysical range was considered for determining the slope classes. As Ahmad et al. (2017) employed, areas having slope with less than 4 degrees (7%) were ranked as 2, the range between 4 degrees (7%) and 9 degrees (16%) as rank 1, and steeper areas of > 9 degrees (16%) were not considered as suitable sites.

Accessibility was weighted as 20%. The road access to the proposed community forestry village is mainly earth roads. In addition, a water reservoir and another village exist within two miles of the proposed village. Thus, such conditions call for road development and subsequently, the village has very good accessibility. Generally, areas closer to roads are more preferred for proposing community forestry. Hence, sites within 300 m of the roads were ranked as 2 (the most suitable sites). Between 300 m and 1,000 m, sites were ranked as 1. Beyond 1,000, sites were treated as unsuitable.

Proximity to a village (settlement), 15% weight, was a contributing factor in selecting the locations of community forestry. User group members usually reached the community forestry sites on a daily basis to cultivate agricultural crops (Hlaing and Inoue 2013). Thus, within 1 mile around a settlement area was considered as the most preferred sites and ranked as 2. According to Community Forestry Instructions (2016), 5-mile distance from the village is eligible for involving a user group in forestation activities. Thus, the distance range between 1 mile and 5 miles of the settlements/village was considered as the second preferred sites and ranked as 1. Locations beyond 5 miles were not considered as suitable in this overlay analysis. In the 10-year reforestation plan of the Forest Department, some community forestry sites are proposed in the reserved forests, but the responsible villages existed outside the community forestry area. Thus, on the condition that accessibility is easy, and a 5-mile distance range is not violated, the community forestry site may be distant from the village. That made this proximity to village criterion was considered as less important comparing to the above-mentioned criteria.

The final criterion was aspect (10 % weight). Like teak plantations, areas having more sunlight were ranked as 2. Areas having limited sunlight were ranked as 1. Flat areas (i.e., water body) were considered as unsuitable.

Table 13. Location selection criteria for community forestry

Criteria	Value	Rank	Weight
Land Cover	Other Wooded Land	2	30%
	Degraded Forest (Bamboo Forest)	1	
	Other Land Cover Classes (Forest, Other Land and Water)	0	
Slope	0-6.99% (0-4 degree)	2	25%
	7%-15.84% (4-9 degree)	1	
	> 15.84% (> 9 degree)	0	
Distance to Roads	0-300 m	2	20%
	300 m – 1,000 m	1	
	> 1,000 m	0	
Proximity to Settlements	0 – 1,609 m (1 mile)	2	15%
	>1,609 m – 8,046 m (5 miles)	1	
	>8,046 m (5 miles)	0	
Aspect	South, West and Southwest	2	10%
	North, East, Southeast, Northeast and Northwest	1	
	Flat (water body)	0	

3.7.2. GIS Model

The model development steps were the same as in assisted natural regeneration. There were two steps (Figure 20 and Figure 21). To determine the suitability classes, sites with value 0 were designated as unsuitable while sites having values > 0 and 1.3 as low suitable, >1.3 and 1.6 as medium suitable, >1.6 and 1.9 as high suitable and >1.9 as very high suitable (Table 14). The minimum size for implementation was 20 ha (approximately 50 acres) and there was no upper limit.

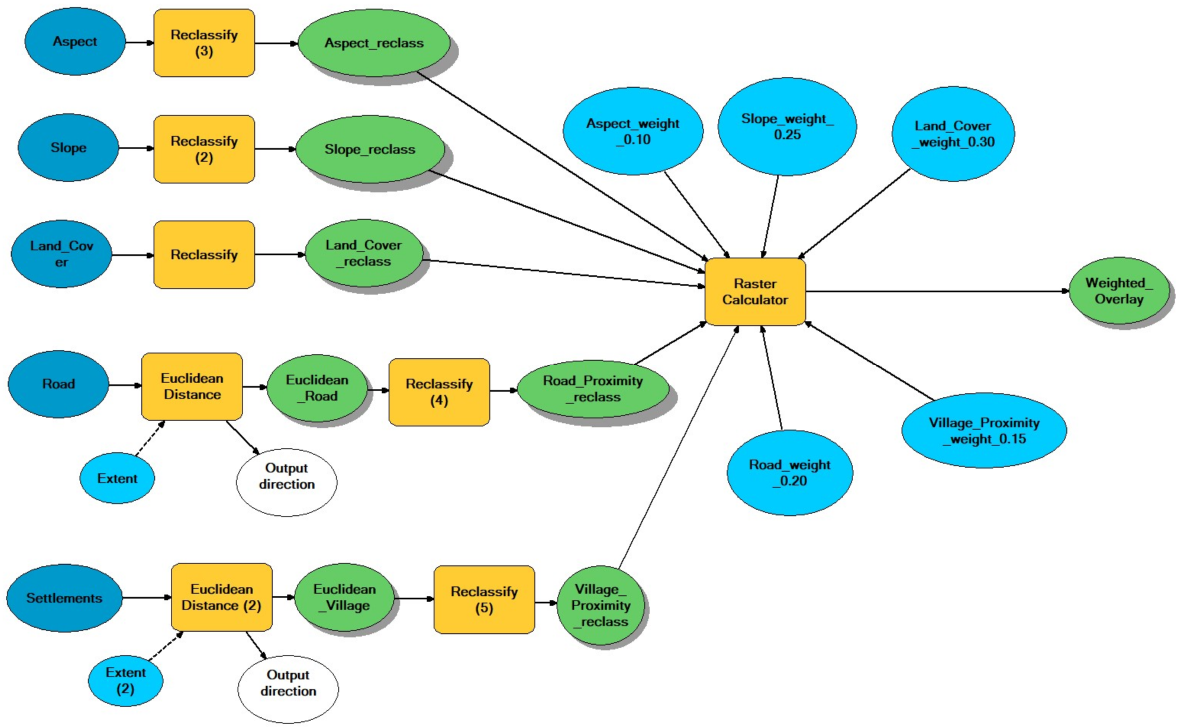


Figure 20. Weighted overlay model for community forestry. The output values ranged from 0 to 2 with continuous (decimal) values in-between.

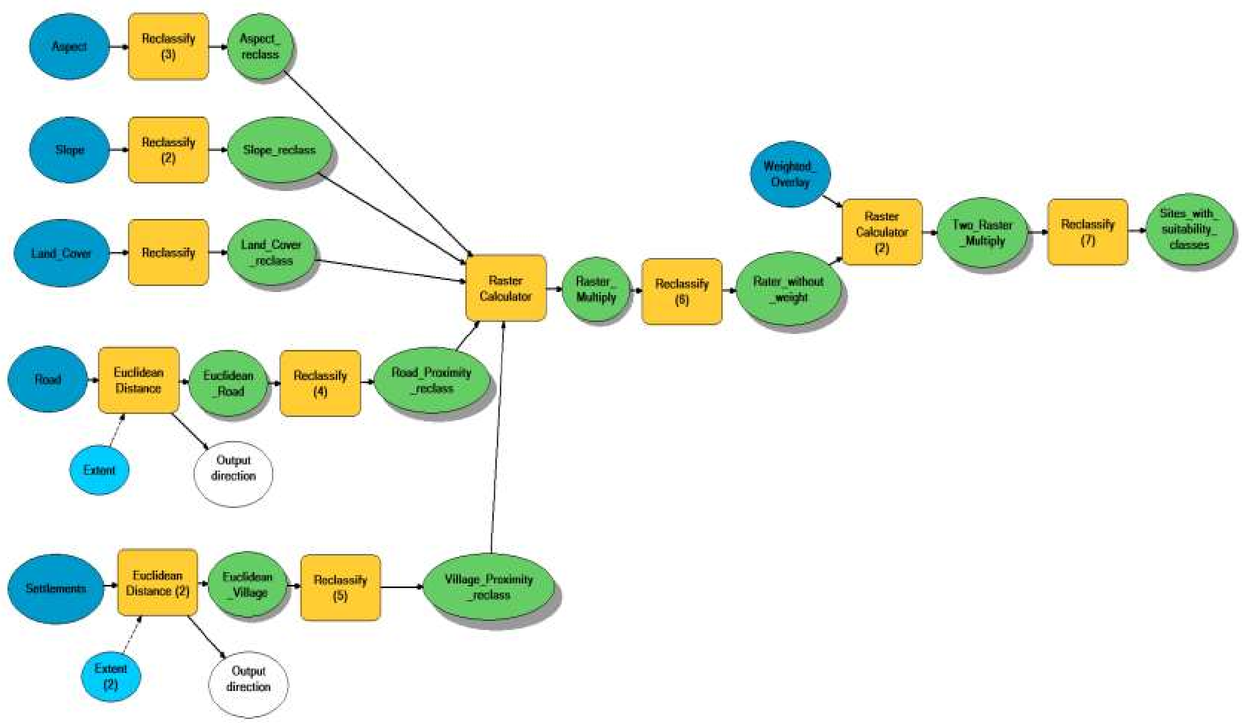


Figure 21. Final model, which integrates the weighted overlay model and the non-weighted overlay model to obtain the end results (i.e., decimal values ranging between 0 and 2).

Table 14. Defining site suitability classes for community forestry

Value Range	Suitability Class
0	Unsuitable
1-1.3	Low
1.3-1.6	Medium
1.6-1.9	High
1.9-2	Very high

3.7.3. Verifying the GIS-suggested Community Forestry Sites with Local Foresters

According to initial consultation with the local foresters, the possible site to set up community forestry was within the South Zamayi reserve forest of the Bago Township. There is an existing village, namely Dawe (Figure 12), that actively participates in reforestation activities of the Forest Department as the plantation labor source. Thus, the local foresters had a positive perspective about their potential contribution in reforestation activities. The two foresters and one office staff provided their field-based and data-based comments on the results of the GIS model.

Like plantations, the GIS-suggested sites may conflict with the existing land use. Thus, before ranking its land suitability status, it was categorized into "already implemented" (in the form of enrichment planting, plantations and assisted natural regeneration) and "available area" based on its existing land use conditions.

The "already implemented" sites (i.e., sites where forest operations have already conducted) were removed. Then, the available sites were obtained, and those available sites were classified into low, medium, high and very high ranked by the local foresters. In addition, areas considered unsuitable were also described in the map.

3.8. Comparing with the Forest Department's Reforestation Plan

The final method applied was scrutinizing the GIS-suggested locations with the freshly developed reforestation plan of the Forest Department. The Forest Department of Myanmar has recently developed a Myanmar reforestation and rehabilitation program (MRRP) for the period between 2017-2018 and 2026-2027. Maps showing targeted locations for plantation establishment, enrichment planting and assisted natural regeneration were described in the plan. Project files were archived in ArcMap platform. Despite the fact that the Forest Department did not employ GIS-aided site suitability analyses for developing the restoration plan, the intention of those ten-year plans overlapped with the objectives of this site selection study.

Therefore, the Forest Department's GIS files were requested so as to compare with this research in addition to obtaining the field-based opinions of responsible foresters. As the study area extended up to three townships of the Bago District, three different local Forest Department offices were simultaneously contacted for data transmission. Comparing those provided data with the results of the GIS model was thoroughly conducted in this study.

CHAPTER 4

RESULTS

This chapter illustrates the results of two separate sections: forest cover change detection, and GIS analysis for determining the locations of three reforestation activities. The results are displayed in order according to the stages applied during the Methods chapter.

In the first section, the accuracies for both 2000 and 2017 Landsat image classification are provided. Then, resultant land cover maps are shown, including quantitative and spatial information. The area compositions of each land cover type for both 2000 and 2017 are compared and land cover changes during the study period are demonstrated in map and matrix formats. Following the forest cover change results, the rates of deforestation and forest degradation are reported.

In the second section, the resultant maps of the flexible and rigid GIS modeling for candidate teak plantation sites are shown. The map derived from overlaying the flexible and rigid GIS models is also provided. Thereafter, by scrutinizing the land use maps of the Forest Department, locations of available land are illustrated. Reclassification of local Forest Department foresters upon the GIS-suggested sites is described as well and the results between foresters' land suitability classification and GIS-modeled classification are compared. The results for assisted natural regeneration and community forestry are similarly presented. Afterwards, a final map integrating the results of three forest operations sites is shown. In the end, the results of this study and the Forest Department's reforestation plan are comparatively shown.

4.1. Image Classification Accuracy Assessment

The overall accuracy of the 2000 classified land cover map is 83% and its standard error is 2.85%. The error matrix for the 2000 classified image is shown in Table 15. Table 16 illustrates the percent area for the 2000 classified image.

The overall accuracy of the 2017 classified land cover map is 87% and its standard error is 2.5%. Table 17 provides the error matrix for the 2017 classified image and Table 18 presents the percent area for the 2017 classified image.

4.2. Land Cover Maps

One of the outputs of this study was the classified land cover maps for both 2000 and 2017 (Figure 22). The 16-year analysis period was between December 2000 and January 2017. During this period, forests declined by 56%, degraded forests/ bamboo forests increased by 35%, other wooded land increased by 94%, other land increased by 198%, and water bodies increased by 94% (Table 19).

The contrast in land cover types between 2000 and 2017 is graphically illustrated in Figure 23. During the study period, the area composition of forest (i.e., areas of forest and degraded forest/ bamboo forest) declined from 91.2% to 82.3% (Figure 24). Conversely, the area composition of non-forest (i.e., other wooded land, other land and water body) increased from 9% to 18%. In Figure 24, two land cover classes: forest and degraded forest/ bamboo forest areas were combined as one category (i.e., forest). The other three such as other wooded land, other land and water body were combined and considered as one category (i.e., non-forest).

Table 15. Error matrix for the 2000 classified image. Its overall accuracy is 83%.

Land Cover Class (Map)	Reference Class					Row Total	User's Accuracy (%)	User's Standard Error
	Forest	Degraded Forest	Other Wooded Land	Others	Water			
Forest	61	9	0	0	0	70	87	4.0
Degraded Forest	12	57	1	0	0	70	81	4.7
Other Wooded Land	1	15	51	3	0	70	73	5.4
Others	0	1	8	41	0	50	82	5.5
Water	2	3	2	1	42	50	84	5.2
Column Total	76	85	62	45	42	310		
Producer's Accuracy (%)	83	84	84	64	100			
Producer's Standard Error	3.8	3.5	10.6	11.9	0			

Table 16. Percent area for the 2000 classified image. This sample-based estimation was calculated using stratified random sampling formula.

Land Cover Class (Map)	Percent Area					Row Total
	Forest	Degraded Forest	Other Wooded Land	Other Land	Water	
Forest	38.764	5.719	0	0	0	44.483
Degraded Forest	8.014	38.067	0.668	0	0	46.749
Other Wooded Land	0.089	1.330	4.523	0.266	0	6.208
Other Land	0	0.013	0.107	0.546	0	0.666
Water Body	0.076	0.114	0.076	0.038	1.591	1.894
Column Total	46.943	45.244	5.373	0.850	1.591	100

Table 17. Error matrix for the 2017 classified image. Its overall accuracy is 87%.

Land Cover Classes (Map)	Reference Class					Row Total	User's Accuracy (%)	User's Standard Error
	Forest	Degraded Forest	Other Wooded Land	Other Land	Water			
Forest	60	10	0	0	0	70	86	4.2
Degraded Forest	7	63	0	0	0	70	90	3.6
Other Wooded Land	2	15	51	1	1	70	73	5.4
Other Land	0	0	9	35	6	50	70	6.5
Water Body	0	0	2	0	48	50	96	2.8
Column Total	69	88	62	36	55	310		
Producer's Accuracy (%)	71	91	95	89	90			
Producer Standard Error	7.1	1.5	1.6	9.9	4.4			

Table 18. Percent area for the 2017 classified image. This sample-based estimation was calculated using stratified random sampling formula.

Land Cover Classes (Map)	Percent Area					Row Total
	Forest	Degraded Forest	Other Wooded Land	Other Land	Water	
Forest	16.599	2.766	0	0	0	19.365
Degraded Forest	6.293	56.638	0	0	0	62.931
Other Wooded Land	0.344	2.580	8.773	0.172	0.172	12.041
Other Land	0	0	0.356	1.386	0.237	1.981
Water Body	0	0	0.147	0	3.533	3.680
Column Total	23.236	61.985	9.277	1.558	3.942	100

Table 19. Summary of classified land cover area for 2000 and 2017

Land Cover Category	2000		2017		Net Change	
	Area (ha)	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
Forest	78,276	44.5	34,077	19.4	-44,199	-56
Degraded Forest	82,264	46.8	110,739	62.9	+28,475	+35
Other Wooded Land	10,924	6.2	21,189	12.0	+10,265	+94
Other Land	1,171	0.7	3,486	2.0	+2,315	+198
Water Body	3,332	1.9	6,476	3.7	+3,144	+94
Total	**175,967**	**100**	**175,967**	**100**		

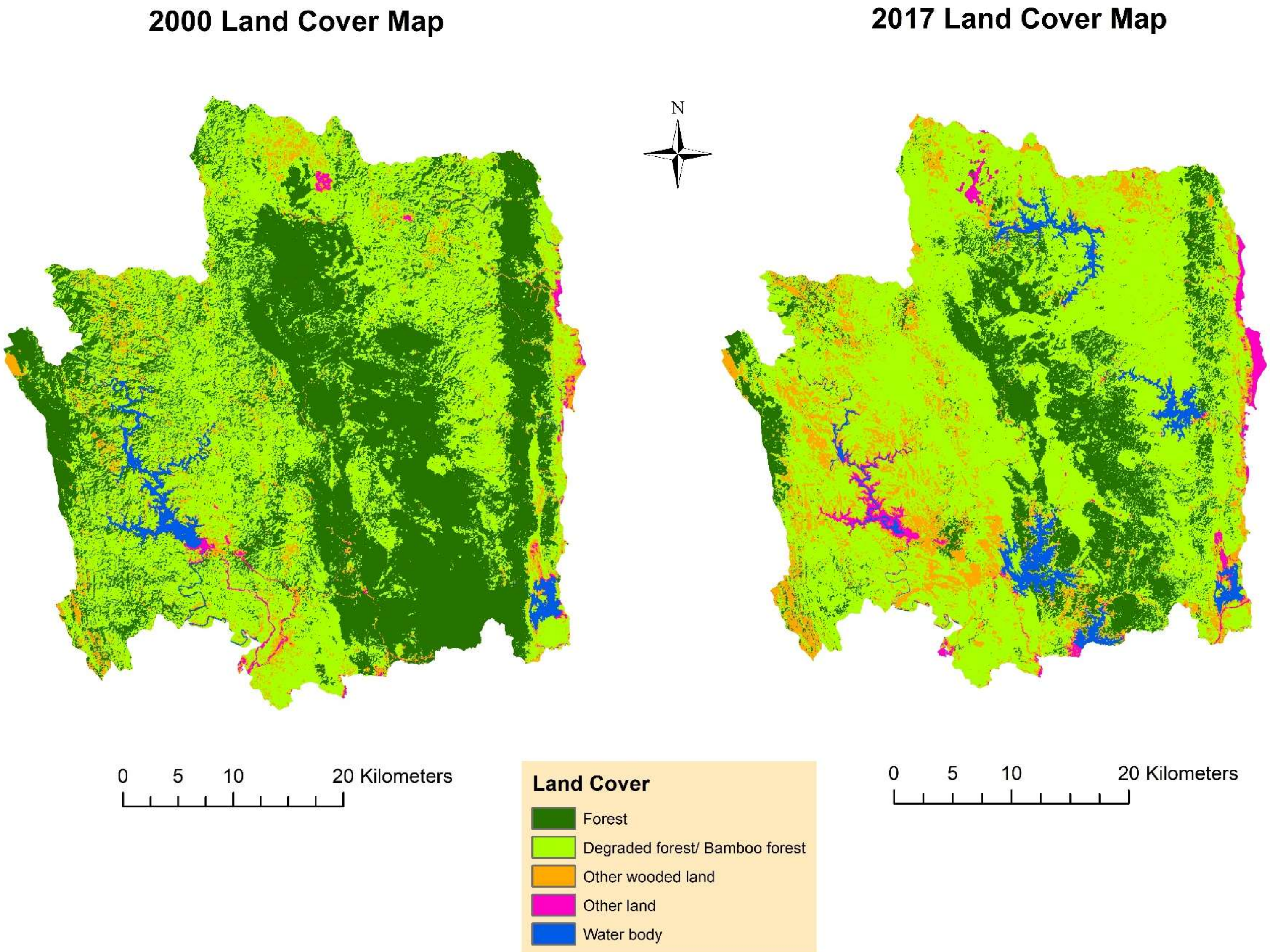


Figure 22. Classified land cover maps for 2000 and 2017

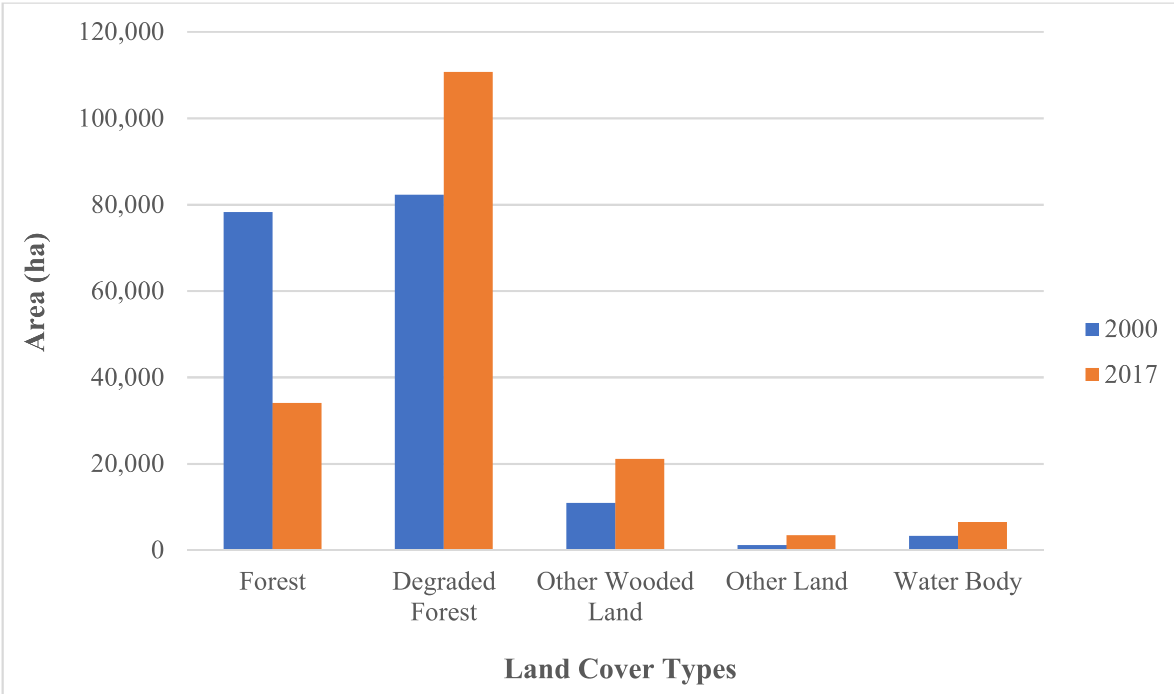


Figure 23. Comparison of area composition of land cover types between 2000 and 2017

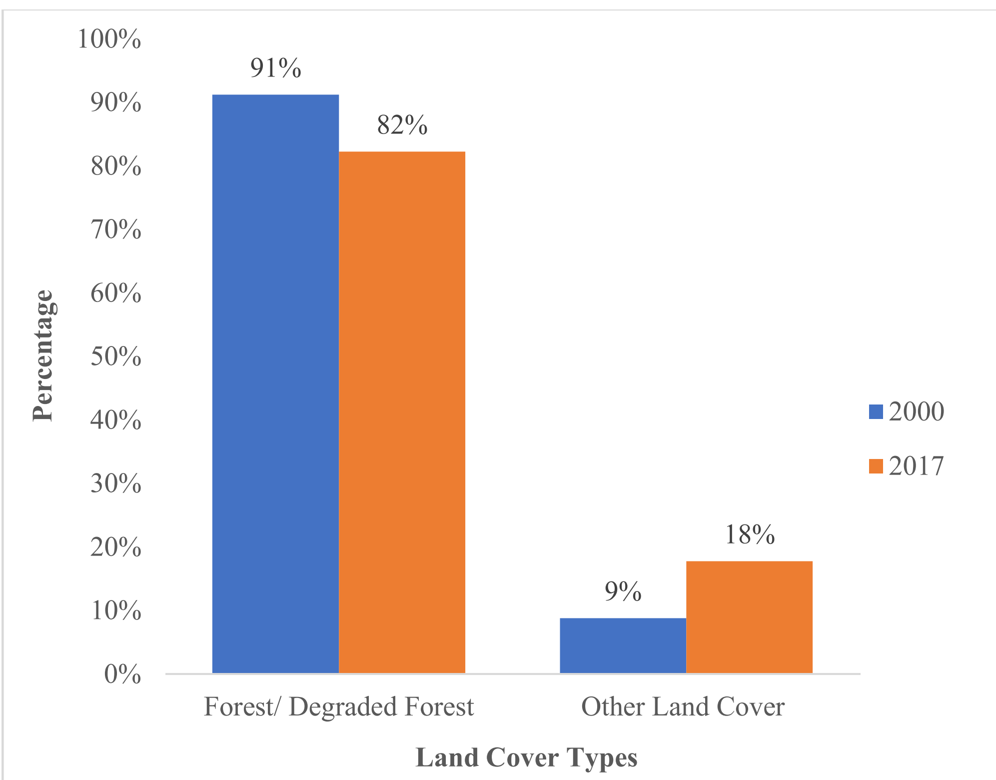


Figure 24. Comparison of area composition between forest and non-forest

4.3. Land Cover Change Detection

Details about land cover changes representing 25 conditions (5 classes x 5 classes) were spatially described in Figure 25. In Figure 25, the first land cover category represents 2000 and the latter is 2017. On the condition that the first category and the latter one is the same, it means that there was no change during the period. The forest to degraded forest conversion was about 38,000 ha and was the greatest during the study period. The second greatest changes were found at conversion from degraded forest to other wooded land and it accounted for approximately 10,800 ha. Table 20 provides the area (ha) for each change in terms of matrix format so that the status of land cover changes can be quantitatively interpreted.

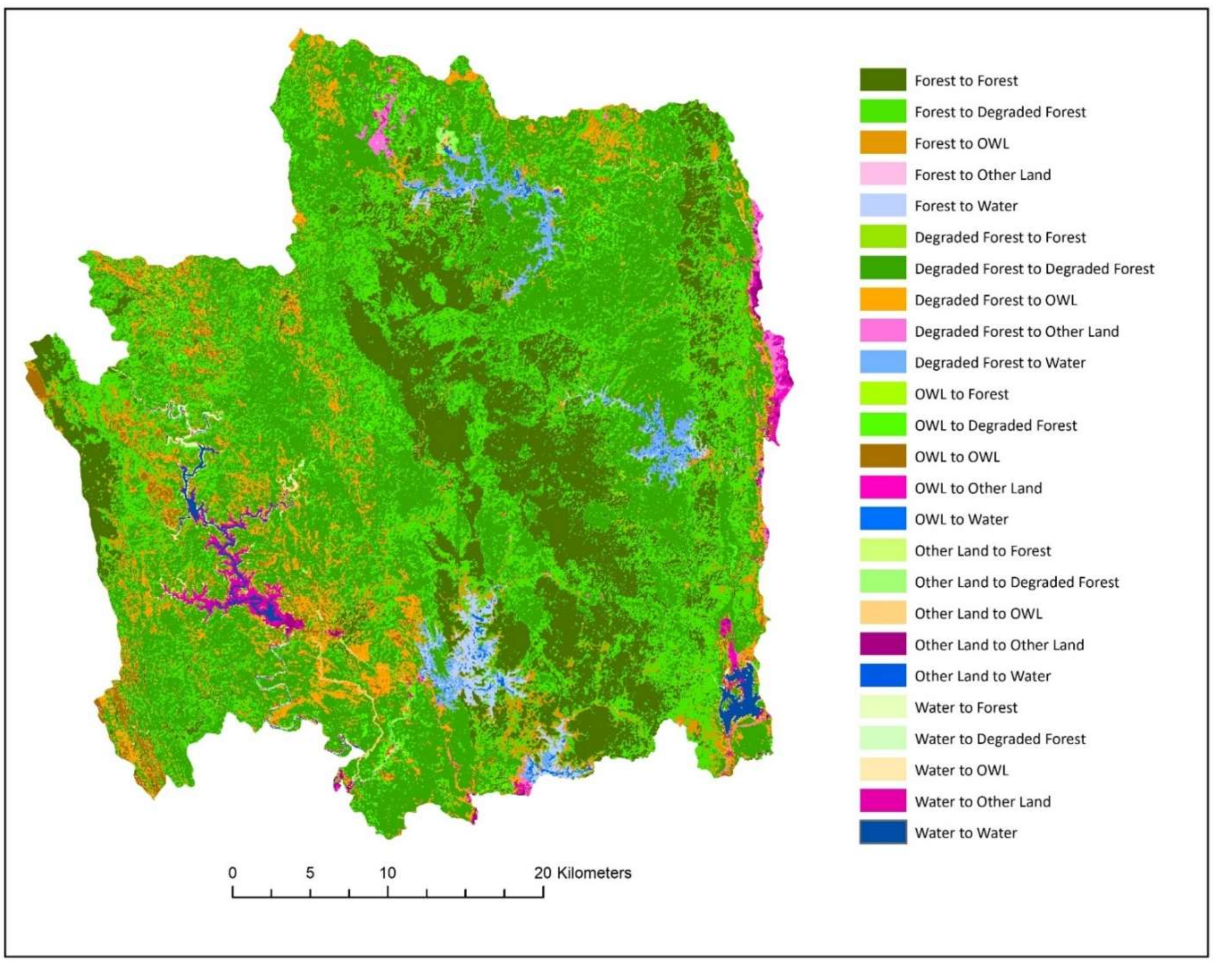


Figure 25. Map showing land cover changes from 2000 and 2017

Table 20. Matrix showing land cover gross changes (ha) between 2000 and 2017

Year: 2000	Year: 2017					
	Forest	Degraded Forest	OWL	Other Land	Water Body	Row Total
Forest	32,522	38,090	5,268	149	2,249	78,278
Degraded Forest	1,228	66,739	10,825	984	2,488	82,264
OWL	256	5,367	4,008	762	531	10,924
Other Land	18	213	408	490	42	1,171
Water Body	54	331	681	1,101	1,165	3,332
Column Total	34,078	110,740	21,190	3,486	6,475	175,969

4.3.1. Forest to Non-forest Changes

The previous results reported changes in each land cover type. This section focuses on maintenance of general forest cover. In this case, forest and degraded forest/ bamboo forest were considered only as one category while the other three classes were taken into account as a non-forest category. The matrix format in Table 21 explains the changes in a quantitative way and Figure 26 is an illustrative map conveying the spatial information about those forest/ non-forest changes. As expected, approximately 160,000 ha of forest area converted to non-forest. Only about 6,000 ha of non-forest area changed into forest. Again, the results of those forest/ non-forest changes are graphically explained in Figure 27.

Table 21. Changes from forest to non-forest (ha) between 2000 and 2017

Year: 2000	Year: 2017		
	Forest/ Degraded Forest	Non-Forest	Total
Forest/ Degraded Forest	138,579	21,963	160,542
Non-Forest	6,239	9,188	15,427
Total	144,818	31,151	175,969

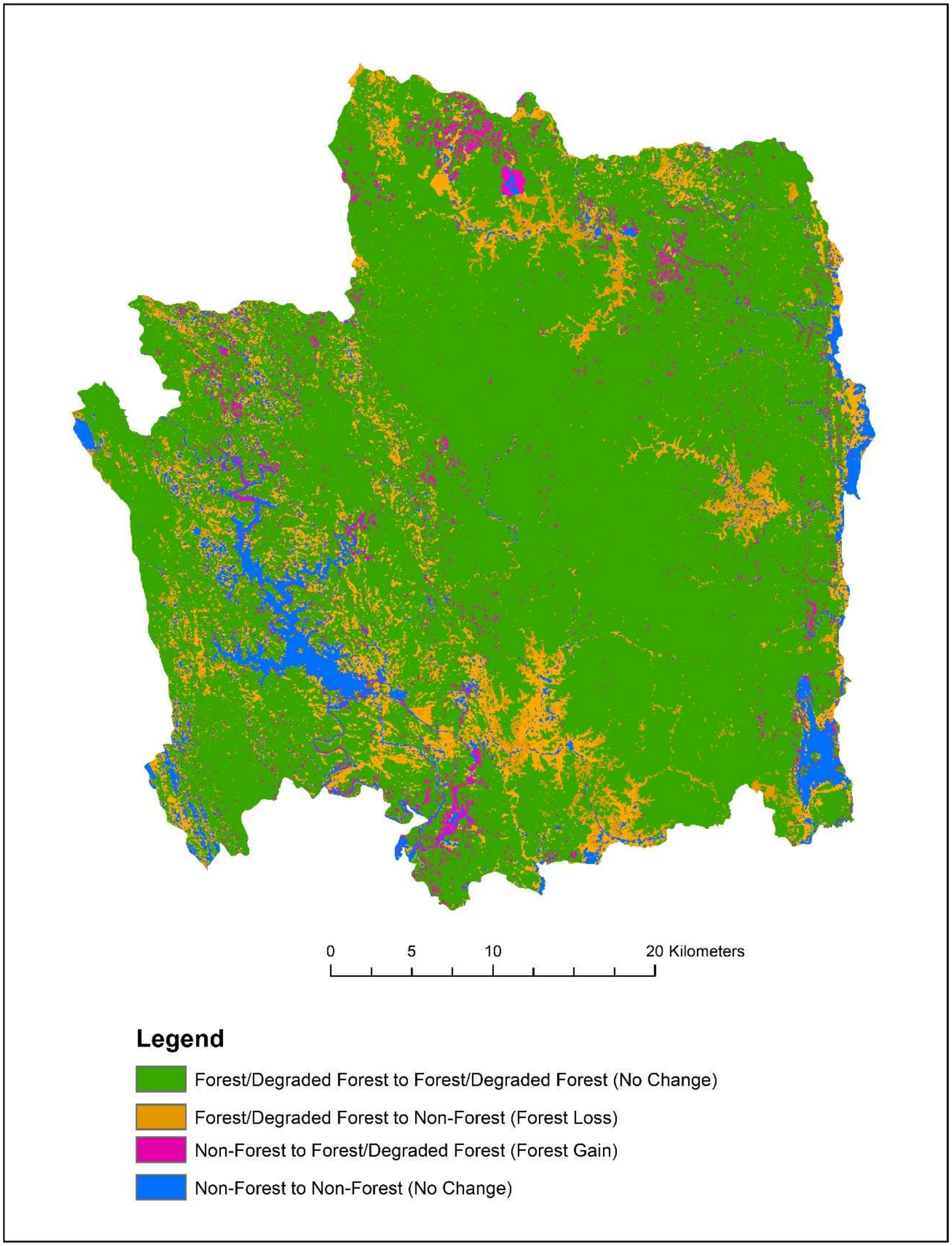


Figure 26. Changes from forest/ degraded forest to non-forest and vice versa between 2000 and 2017. If the first category and the second are the same, it means that there is no change in those areas during the study period.

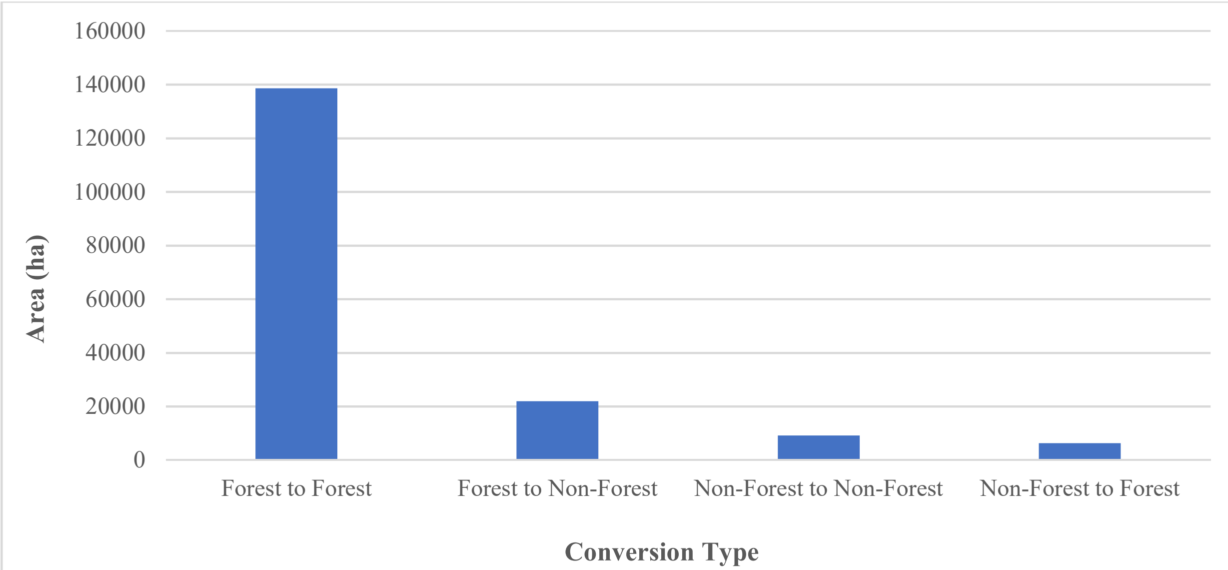


Figure 27. Conversion from forest to non-forest and vice versa between 2000 and 2017. Forest to Forest implies that there is no change. Forest here refers to the combined areas of Forest and Degraded Forest. Non-Forest means other land cover classes except Forest

4.3.2. Rate of Forest Cover Changes between 2000 and 2017

The results indicate that between December 2000 and January 2017, the annual rate of forest degradation (i.e., conversion from forest to degraded forest/ bamboo forest) was 1.35% (Table 22). The annual deforestation (conversion from forest and degraded forest/ bamboo forest to other land cover classes) rate was 0.78% (Table 23). The annual rate of forest gain was 0.22% (Table 24). Therefore, it could be deduced that the forest degradation rate was much higher than the deforestation rate in the study area.

Table 22. Annual forest degradation rate between December 2000 and January 2017

Forest Loss (Forest Degradation)	Area (ha)	% of Total Area (175,969 ha)	Annual Rate of Forest Degradation (%)
Forest to Degraded Forest	38,090	21.65	1.35
Total	**38,090**	**21.65**	**1.35**

Table 23. Annual deforestation rate between December 2000 and January 2017

Forest Loss (Deforestation)	Area (ha)	% of Total Area (175,969 ha)	Annual Rate of Deforestation (%)
Forest to Other Wooded Land	5,268	2.99	0.19
Forest to Other Land	149	0.08	0.01
Forest to Water	2,249	1.28	0.08
Degraded Forest to Other Wooded Land	10,825	6.15	0.38
Degraded Forest to Other Land	984	0.56	0.03
Degraded Forest to Water	2,488	1.41	0.09
Total	**21,963**	**12.47**	**0.78**

Table 24. Annual rate of forest gain between December 2000 and January 2017

Forest Gain	Area (ha)	% of Total Area (175,969 ha)	Annual Rate of Forest Gain (%)
Other Wooded Land to Forest	256	0.15	0.009
Other Wooded Land to Degraded Forest	5367	3.05	0.191
Other Land to Forest	18	0.01	0.001
Other Land to Degraded Forest	213	0.12	0.008
Water Body to Forest	54	0.03	0.002
Water Body to Degraded Forest	331	0.19	0.012
Total	**6,239**	**3.55**	**0.223**

4.4. GIS Modeling- Sites for Teak Plantations

One of the objectives of the GIS modeling was to determine candidate areas for individual reforestation activities based on the ecological requirements of teak. The former results about forest cover change show that deforestation and forest degradation has been happening in the study area. Artificial regeneration in terms of plantation establishment is the forestry activity that can help intensively and extensively in reforestation. Two models (flexible and rigid) were developed to present the spatial information about teak plantation establishment.

4.4.1. Flexible GIS Model

The flexible GIS model provides a broad range of possible operational teak plantation sites (Figure 28). Based on the composition of each suitability class (i.e., unsuitable (water body), unsuitable, low, medium, high and very high), only 5% of the study area was found as unsuitable (1% was dense forest and 4% was water body) (Figure 29).

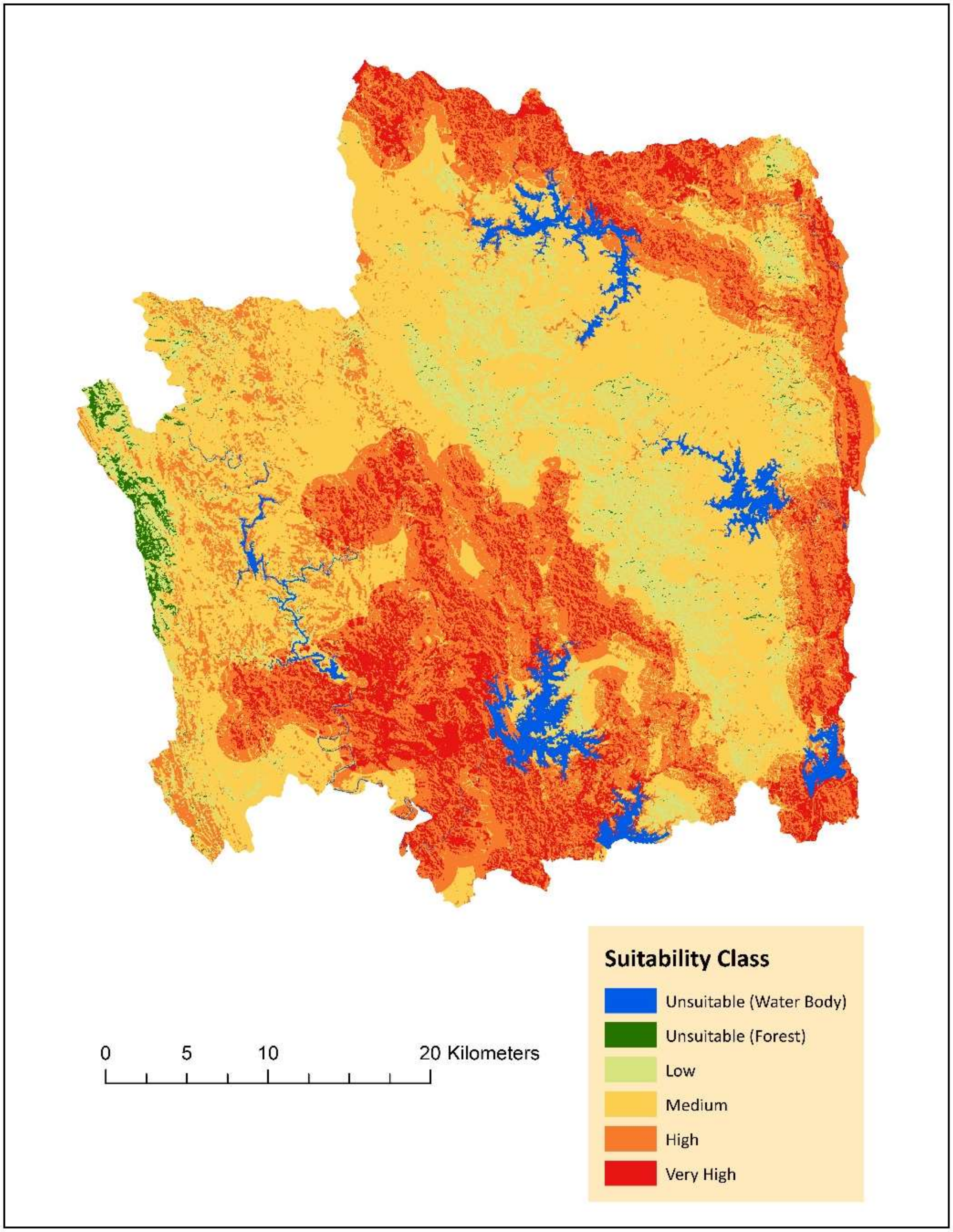


Figure 28. Suitable sites for teak plantations generated by the flexible GIS model. Using the flexible approach reveals results in terms of zonation format. Unsuitable class includes water body and dense forest areas.

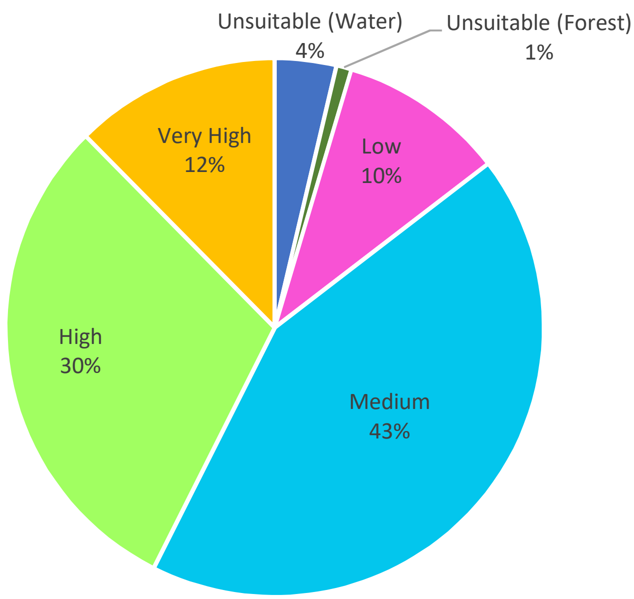


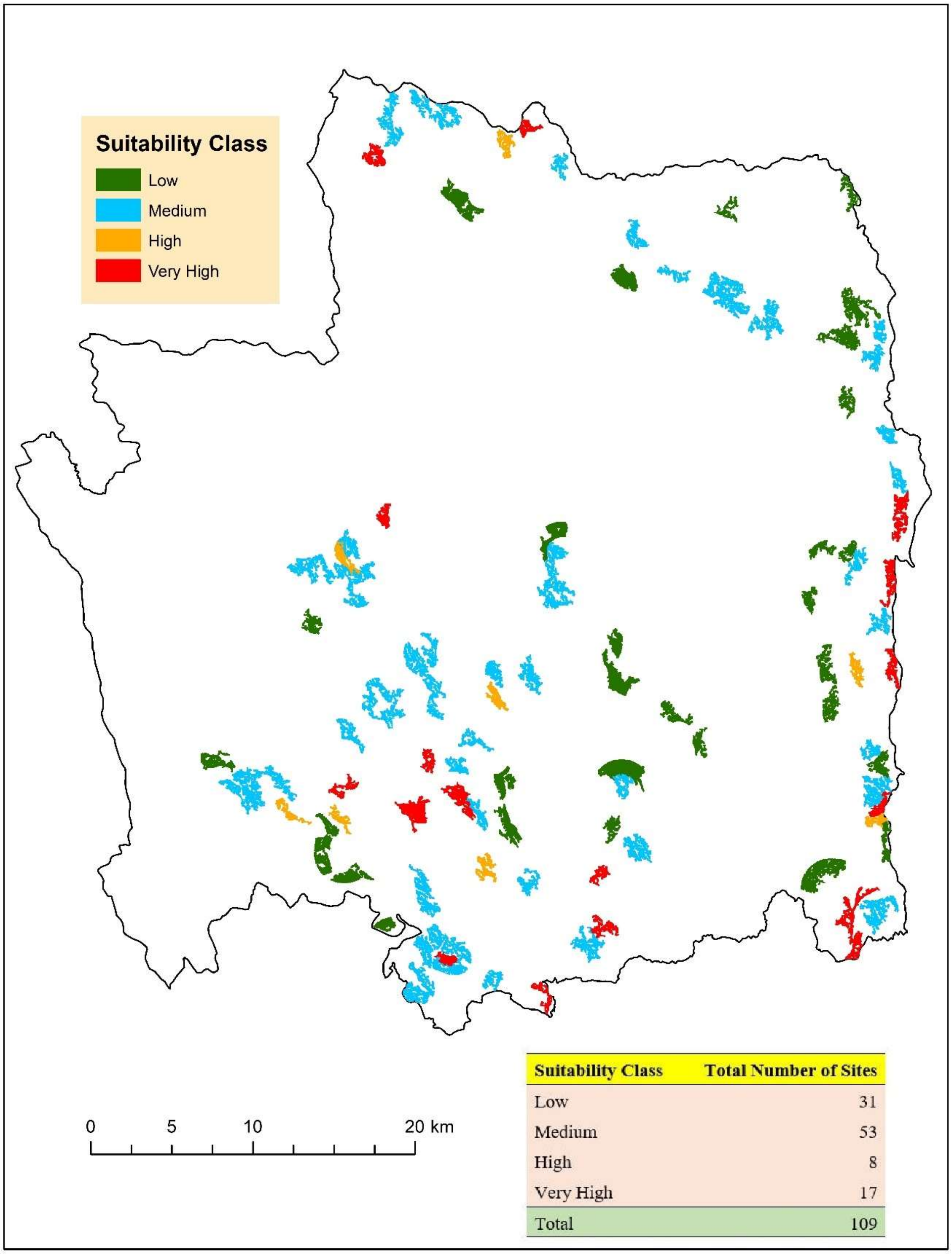
Figure 29. Composition of site suitability classes for teak plantation establishment resulted from flexible GIS model

4.4.2. Rigid GIS Model

The rigid GIS model pinpointed the proposed teak plantation sites more precisely than the flexible model. This model generated a total of 109 sites, covering only 4.41% of the total study area (Figure 30). The sites were ranked by suitability classes as follows: 31-low, 53-medium, 8-high and 17-very high.

4.4.3. Overlay of the Rigid GIS Model on the Flexible GIS Model

Although much more selective, the proposed sites generated from the rigid GIS model with the most suitable zones (i.e., high and very high suitability classes) of the flexible model (Figure 31).



Suitability Class	Total Number of Sites
Low	31
Medium	53
High	8
Very High	17
Total	109

Figure 30. Suitable sites for teak plantations generated by the rigid GIS model.

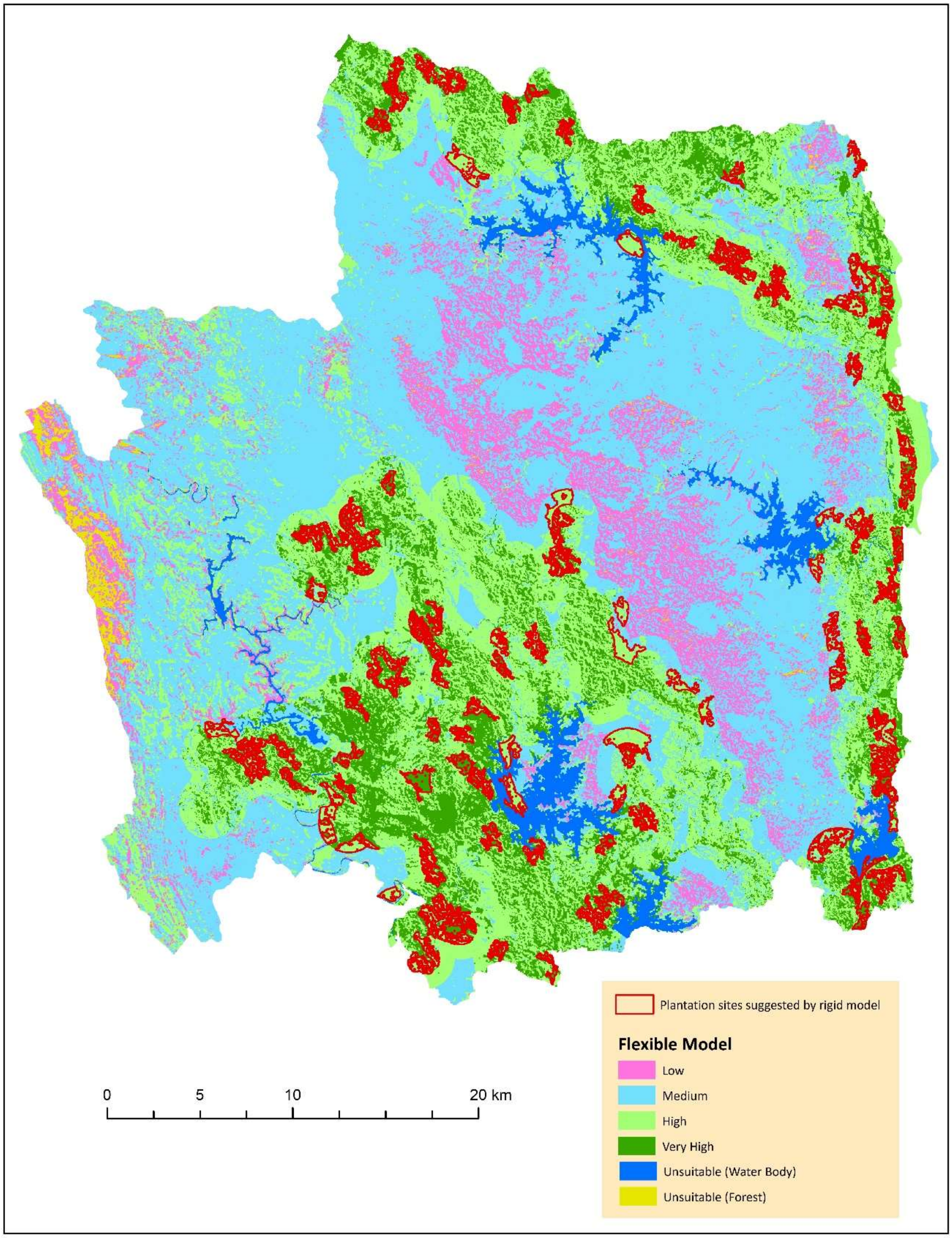


Figure 31. Overlay of the rigid GIS model results on the flexible GIS model results. The results of the rigid model fall within the most suitable zones (i.e., suitability class: high and very high) of the flexible model.

4.4.4. Availability of Land for GIS-suggested Sites

The results of the rigid GIS model were cross-referenced with the existing land use data available at the local office of the Forest Department and then reviewed by experienced local foresters to further assess suitability status. Of the 109 sites, there were 33 sites categorized as "already planted", 13 sites as "planted but need to be restored" and 63 sites "not yet planted". In other words, it implied that 30% of the GIS-recommended sites had been planted and the remaining 70% were available for teak plantation establishment and re-establishment (Figure 32). The "planted but need to be restored" describes sites that were planted in the past, but were not successful, requiring restoration. Thus, elimination of the "already planted" sites and summation of the latter two categories resulted in 76 sites as available areas for teak plantations (Figure 33).

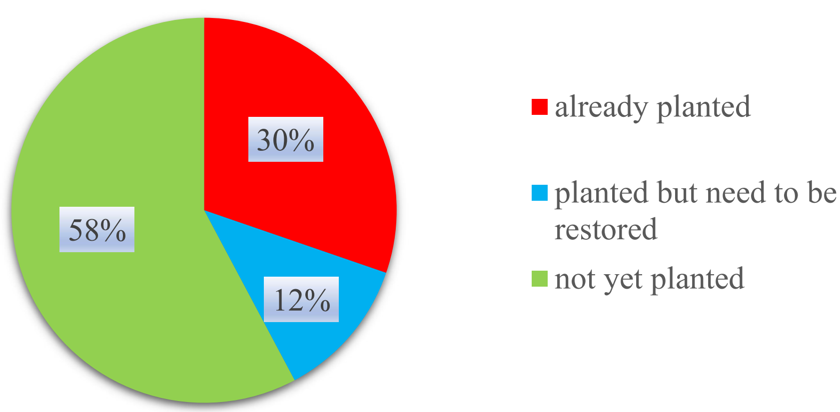
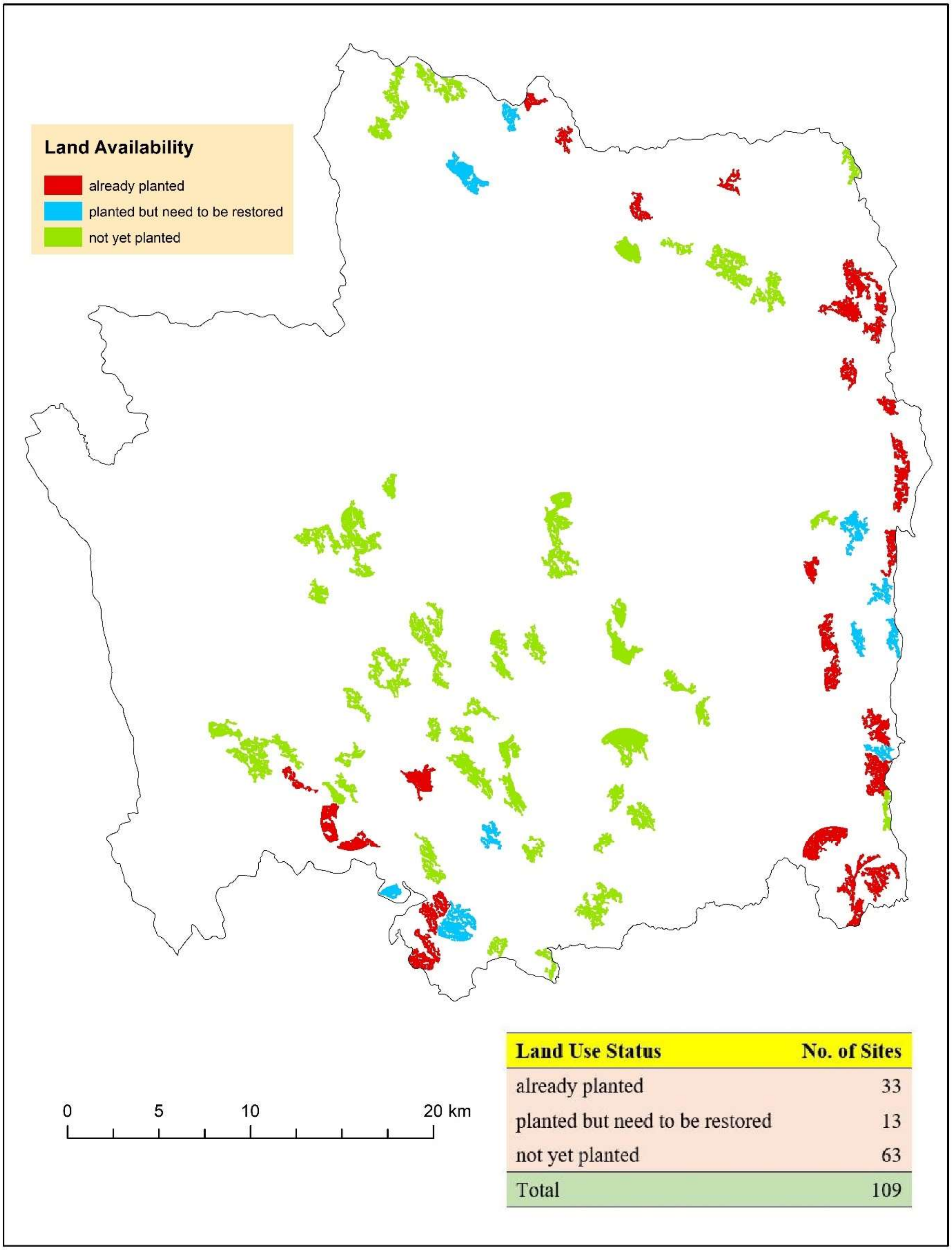


Figure 32. Availability of land for teak plantation establishment. It is calculated based on 109 sites which is suggested by rigid GIS model. Removing planted 33 sites resulted in 76 sites as available areas for teak plantations.



Land Use Status	No. of Sites
already planted	33
planted but need to be restored	13
not yet planted	63
Total	109

Figure 33. Previously planted sites and available sites for teak plantations establishment

4.4.5. Local Foresters' Re-ranking on GIS-based Suitability Classes

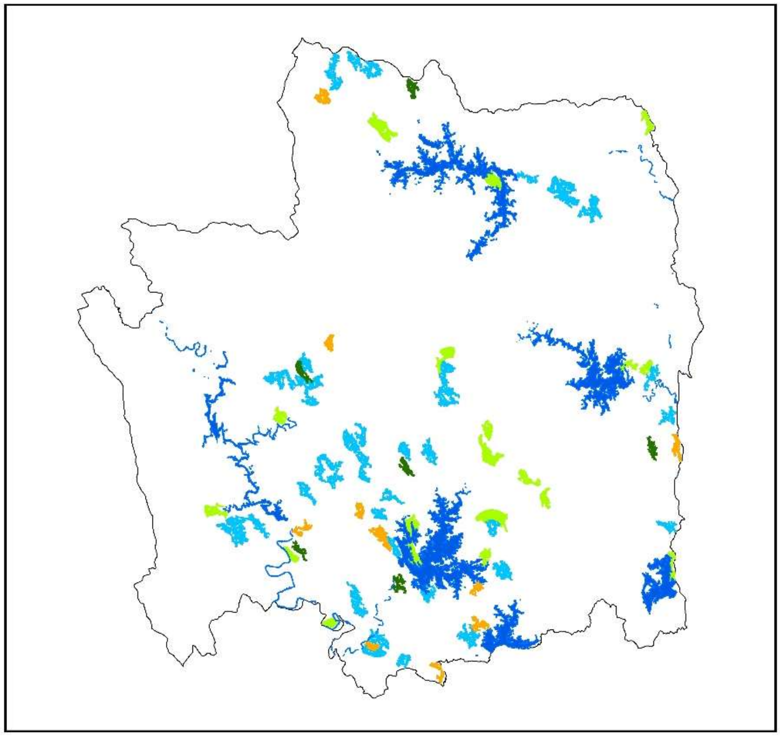
Among the 76 available sites (Figure 33), in terms of land suitability indices, there were 19 sites classified as low, 41 as medium, 6 as high and 10 as very high according to the model. Upon further review with local foresters, 9 sites were classified as unsuitable, 25 sites as low, 23 sites as medium, 8 sites as high and 11 sites as very high (Figure 34).

Even though local foresters argued 9 sites as unsuitable (Table 25), the other 67 sites were agreed as suitable sites for teak plantations except reclassifying their land suitability classes (Figure 35).

Table 25. Matrix reporting the composition of site suitability classes between GIS-based and local foresters' classification for teak plantations

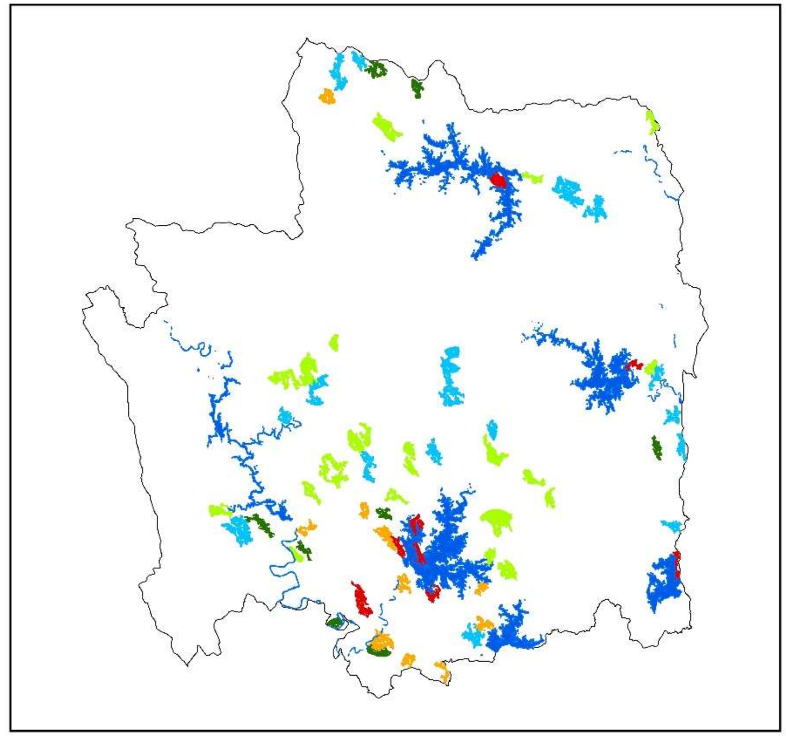
GIS Suitability	**Foresters' Suitability Classes**					
Classes	**Unsuitable**	**Low**	**Medium**	**High**	**Very High**	**Row Total**
Low	5	10	3	1	0	19
Medium	4	12	19	4	2	41
High	0	2	0	3	1	6
Very High	0	1	1	0	8	10
Column Total	9	25	23	8	11	76

Suitability Class generated by GIS



Suitability Class	No. of Sites
Low	19
Medium	41
High	6
Very High	10
Total	76

Suitability Class provided by Local Foresters



Suitability Class	No. of Sites
Unsuitable	9
Low	25
Medium	23
High	8
Very High	11
Total	76

Figure 34. Site suitability classes for teak plantations generated by GIS versus determined by local foresters

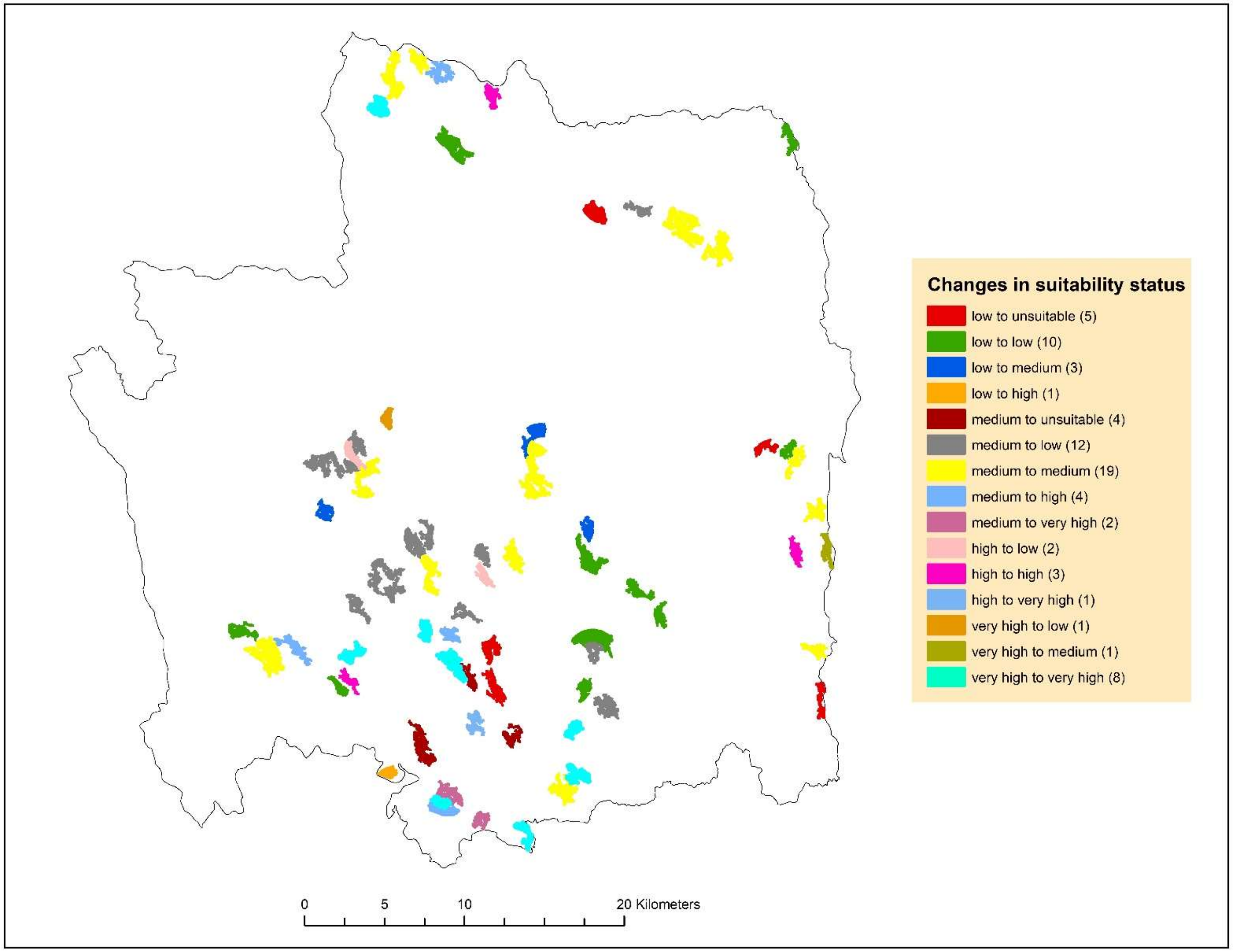


Figure 35. Map showing suitability class change status. The first suitability class was generated by GIS and the second (latter) one was provided (reclassified) by foresters. If the first and second classes are the same, it means that foresters agree with the GIS results. The numbers in the parentheses represent the total number of teak plantation sites. There are 76 sites in total.

4.4.6. Justification of Local Foresters on Customizing the GIS-based Site Suitability Classes for Teak Plantation Establishment

According to GIS results, there were a total of 109 sites suggested for teak plantation establishment. Thus, large-scale maps displaying the 109 sites with corresponding site IDs (Figure 36**,** Figure 37, Figure 38 and Figure 39) were displayed to better navigate the locations of each site that were linked with the justification table (Appendix A). Four maps were provided, one map for each reserved forest.

The justification table was developed through obtaining the opinions of local Forest Department foresters on the GIS results. Foresters modified the GIS results based on their expert perspectives. Consequently, the GIS results and the foresters' re-ranks on land suitability classes were comparatively reported with justifications.

Foresters defined 9 sites as inappropriate because they were very close to dams, and one site almost overlapped with the existing established plantations.

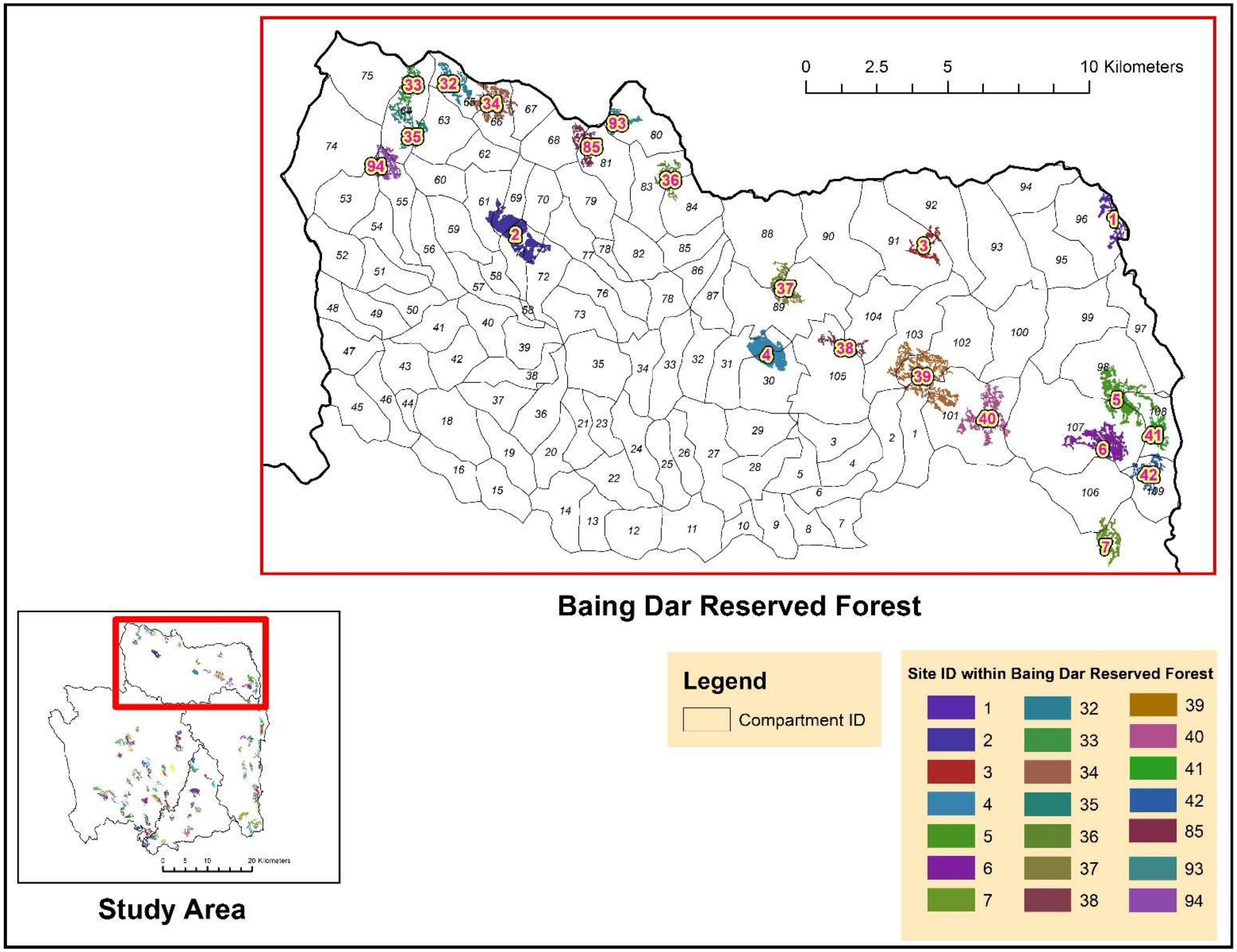


Figure 36. GIS-suggested sites with ID numbers for Baing Dar reserved forest. There are 20 sites completely falling within Baing Dar and 1 site (ID 7) is in both Baing Dar and nearby reserved forest (Kawliya). Compartment numbers are also labeled.

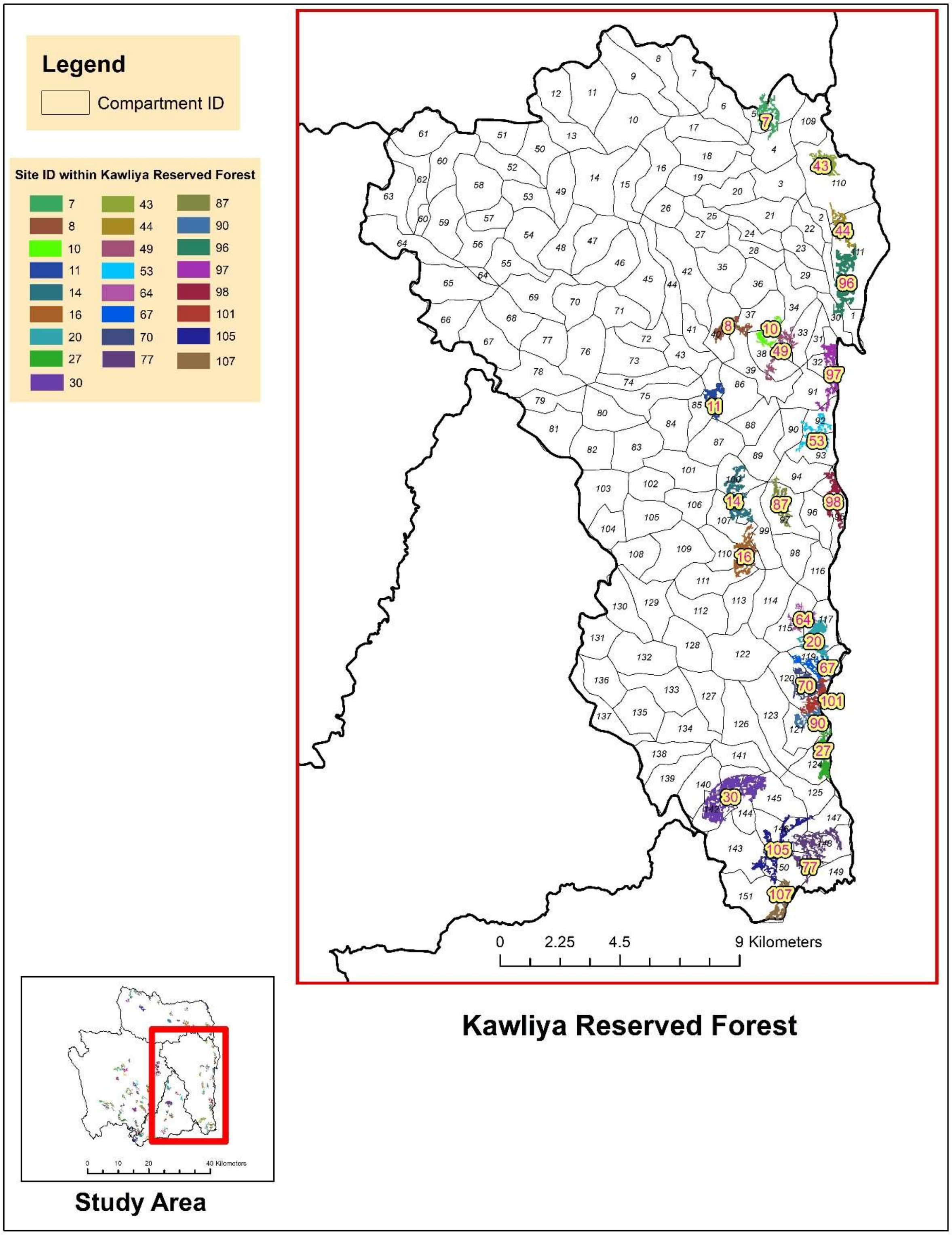


Figure 37. GIS-suggested sites with ID numbers for Kawliya reserved forest. There are 24 sites completely falling within Kawliya and 1 site (ID 7) is in both Kawliya and nearby reserved forest (Baing Dar). Compartment numbers are also labeled.

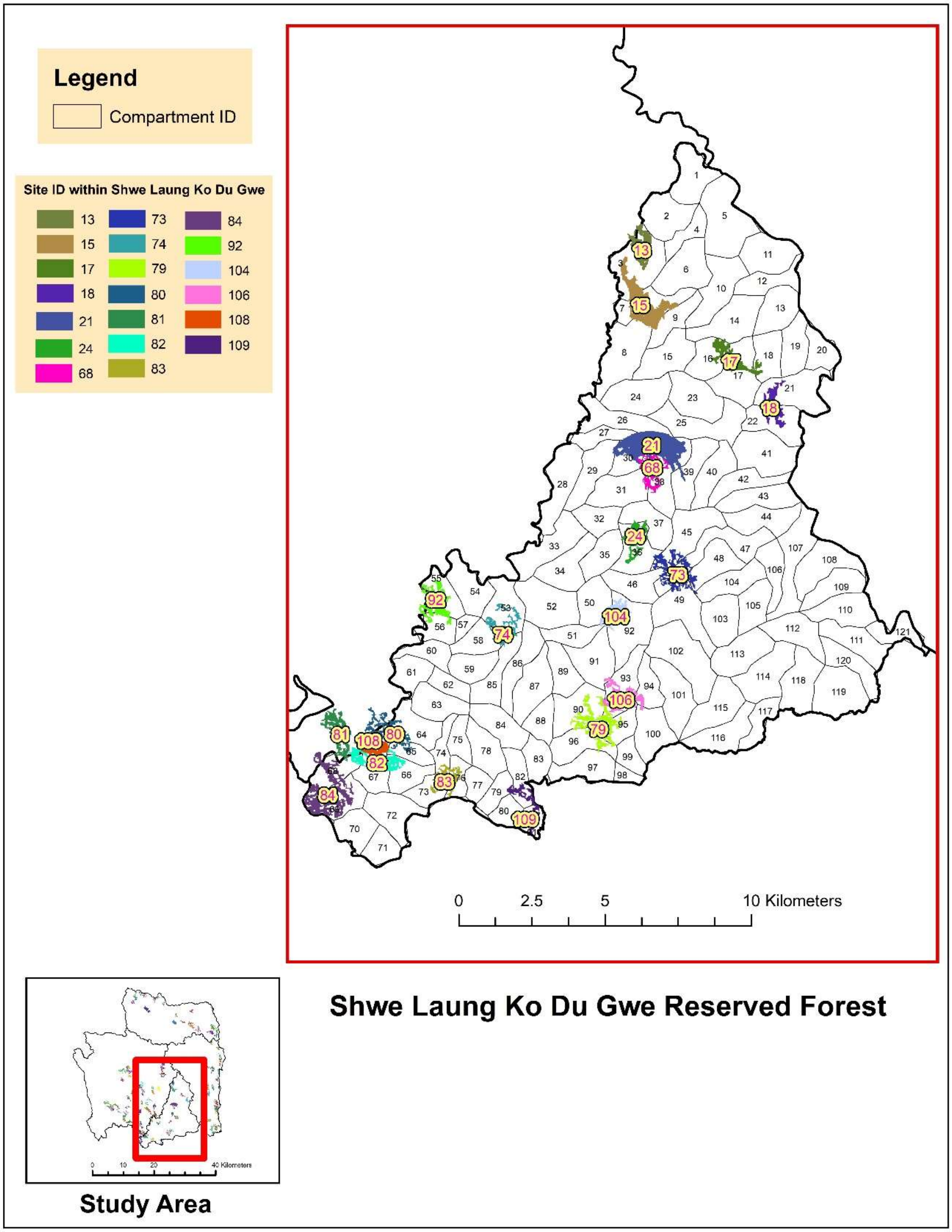


Figure 38. GIS-suggested sites with ID numbers for Shwe Laung Ko Du Gwe reserved forest. There are 13 sites completely falling within Shwe Laung Ko Du Gwe and 7 sites (ID 13, 80, 81, 82, 84, 92 and 108) are in both Shwe Laung Ko Du Gwe and nearby reserved forest (South Zamayi). Compartment numbers are also labeled.

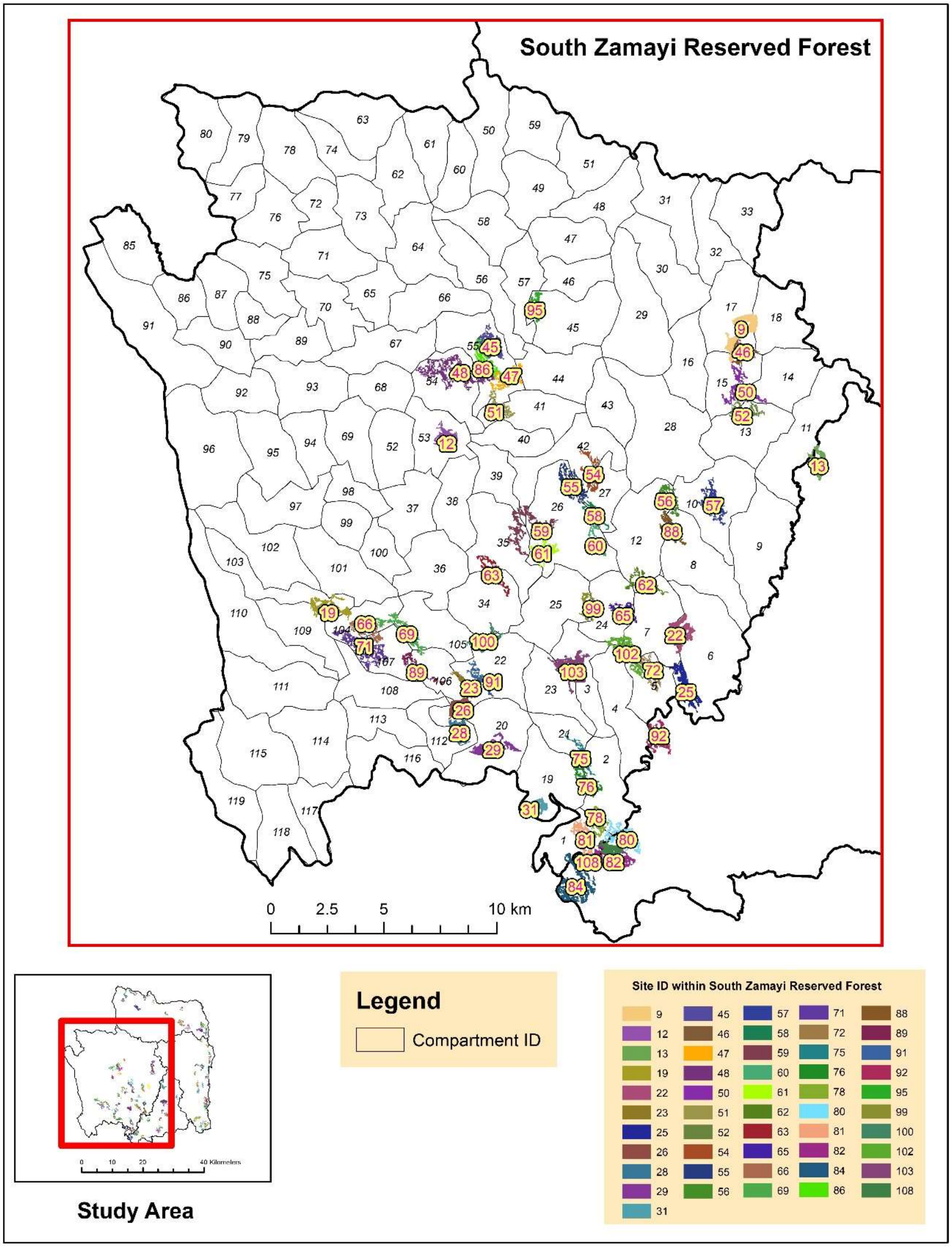


Figure 39. GIS-suggested sites with ID numbers for South Zamayi reserved forest. There are 44 sites completely falling within South Zamayi and 7 sites (ID 13, 80, 81, 82, 84, 92 and 108) are in both South Zamayi and nearby reserved forest (Shwe Laung Ko Du Gwe). Compartment numbers are also labeled.

4.5. GIS Modeling- Sites for Assisted Natural Regeneration

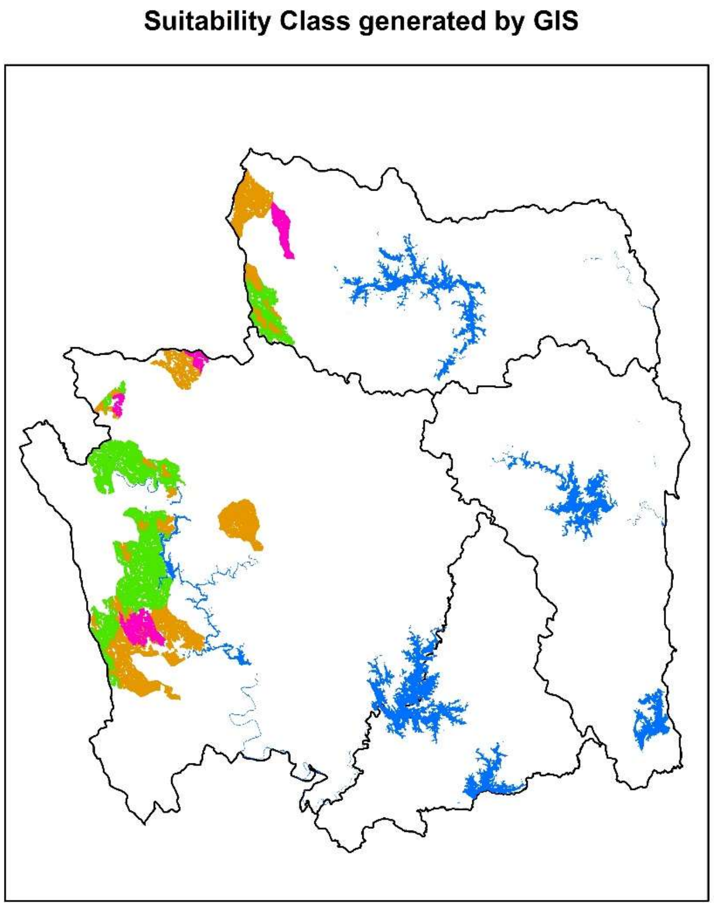
To determine potential areas for natural regeneration, five criteria were used such as logging intensity, land cover, slope, distance to roads and aspect. In addition, the minimum size was set to 20 ha. The integration of the weighted and non-weighted overlay modeling was applied, which was the same as the rigid model for teak plantations. According to the integrated GIS model, there was a total of 41 potential natural regeneration sites (Figure 40) that had the minimum area of 20 ha. Among the 41 sites, the suitability class rankings are as follows: 10-low, 27-medium and 4-high. The total area of the sites represents 4.75% of the entire study area.

4.5.1. Local Foresters' Re-ranking on GIS-based Suitability Classes

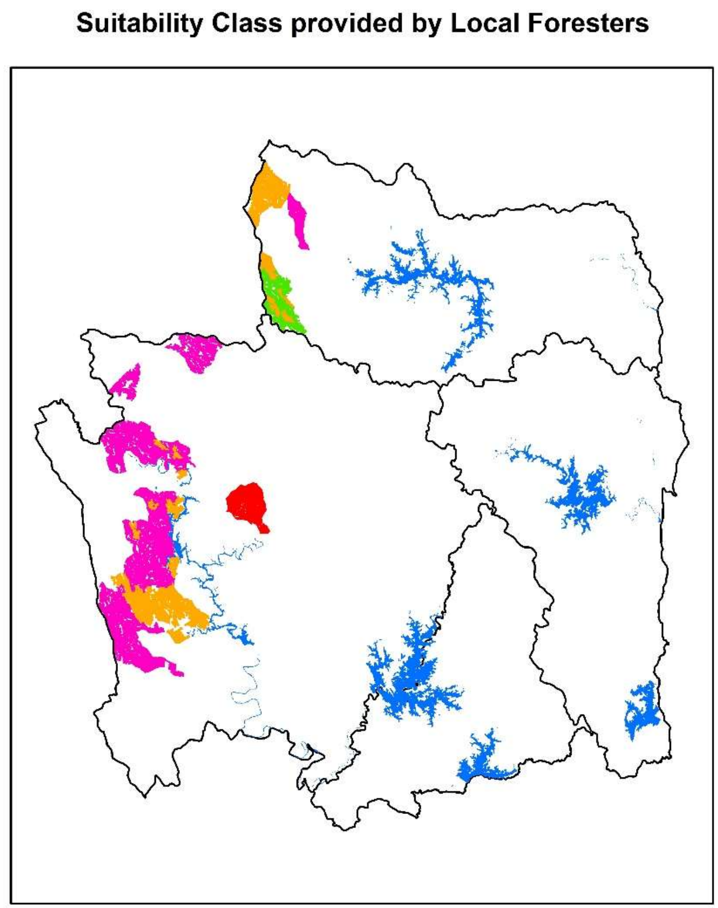
Foresters reclassified the GIS-based site suitability ratings as follows: 1 site ranked as low, 21 sites as medium, 18 sites as high and 1 site had assisted natural regeneration implemented in 2014 (Figure 40). Unlike teak plantations, the foresters did not judge any of the GIS-suggested sites as unsuitable. Generally, they agreed with the results of the GIS model, only re-ranking the site suitability classes (Figure 41). The comparison of land suitability classes between GIS-based and foresters' ranking was presented in terms of a matrix (Table 26).

Table 26. Matrix reporting the composition of site suitability classes between GIS-based and local foresters' classification for assisted natural regeneration

GIS Suitability	Foresters' Suitability Classes				
Classes	**Implemented**	**Low**	**Medium**	**High**	**Row Total**
Low	0	1	3	6	10
Medium	1	0	17	9	27
High	0	0	1	3	4
Column Total	1	1	21	18	41



Suitability Class	No. of Sites
Low	10
Medium	27
High	4
Total	41



Suitability Class	No. of Sites
Low	1
Medium	21
High	18
Already Implemented	1
Total	41

Figure 40. Site suitability classes for assisted natural regeneration generated by GIS versus determined by local foresters.

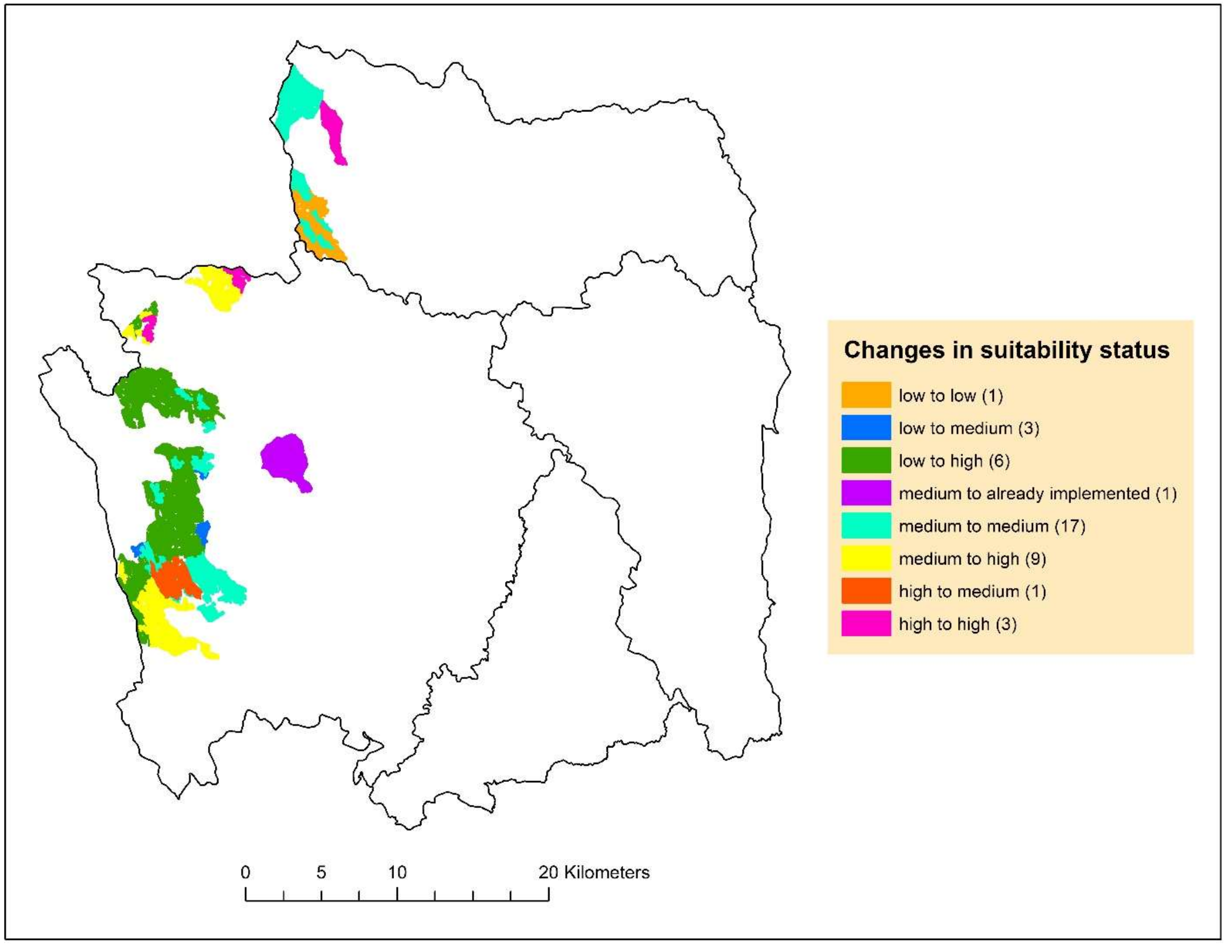


Figure 41. Map showing suitability class change status. The first suitability class was generated by GIS and the second (latter) one was provided (reclassified) by foresters. If the first and second classes are the same, it means that foresters agree with the GIS results. The numbers in the parentheses represent the total number of assisted natural regeneration sites. There are 41 sites in total.

4.5.2. Justifications of Local Foresters on Customizing the GIS-based Site Suitability Classes for Assisted Natural Regeneration

Foresters justified why they re-ranked the GIS-based suitability classes for assisted natural regeneration. According to GIS, there were 41 sites generated. Thus, large-scale maps showing all 41 sites with respective site IDs (Figure 42 and Figure 43) were illustrated to easily navigate each site. Such locator maps with site IDs were tied up with the justification table (Appendix B). As there were only two reserved forests recommended for assisted natural regeneration, two large-scale maps were provided, one map for each reserved forest.

Among the GIS results, there were 41 sites and only 1 site has been naturally regenerated according to the forest operations records of the Forest Department. It was concluded that foresters agreed that all the GIS-suggested sites were suitable for assisted natural regeneration. Like plantations, they just redefined the suitability ranks resulted from the GIS model.

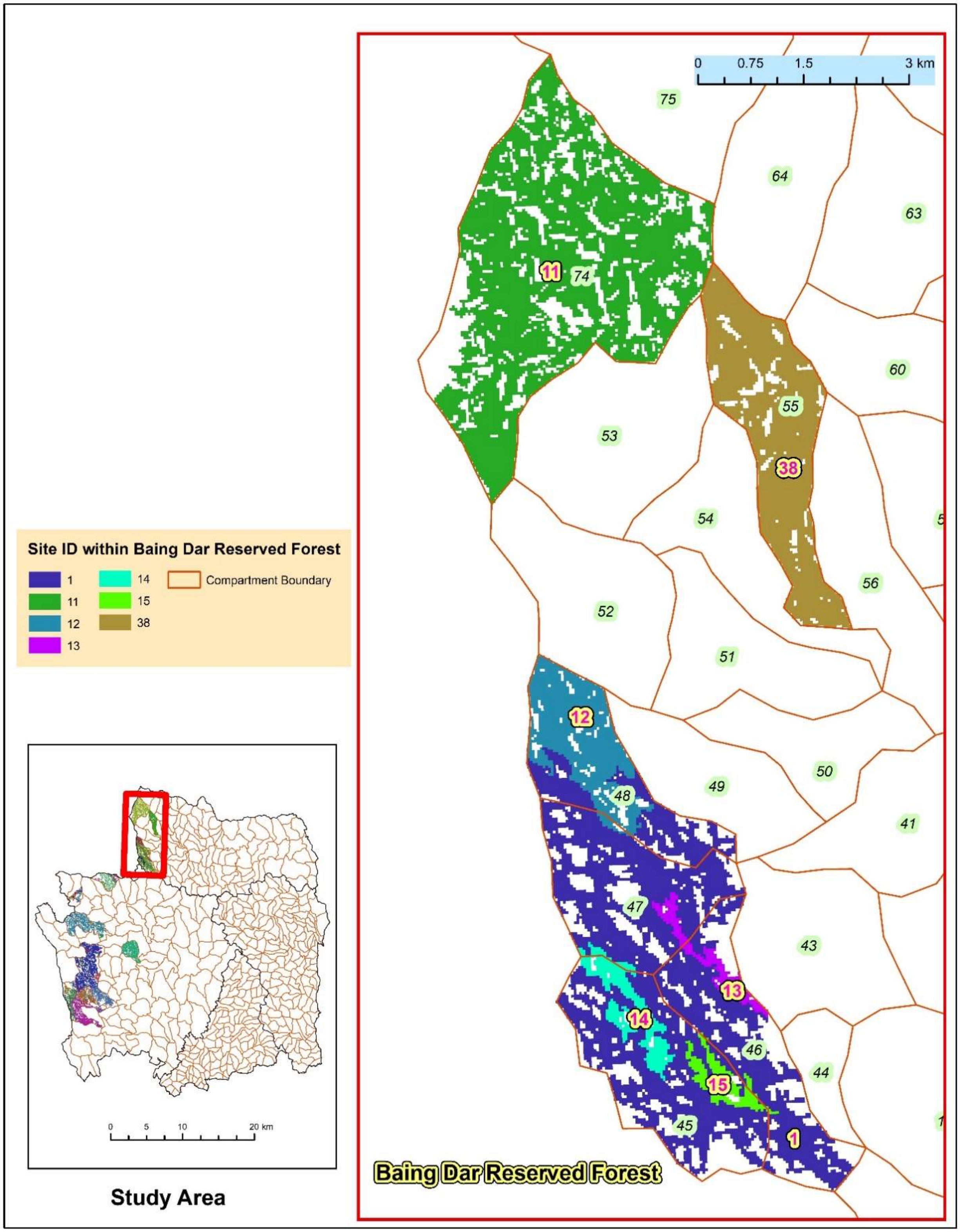


Figure 42. GIS-suggested sites with ID numbers for Baing Dar reserved forest. There is a total of 7 sites. Compartment numbers are also labeled.

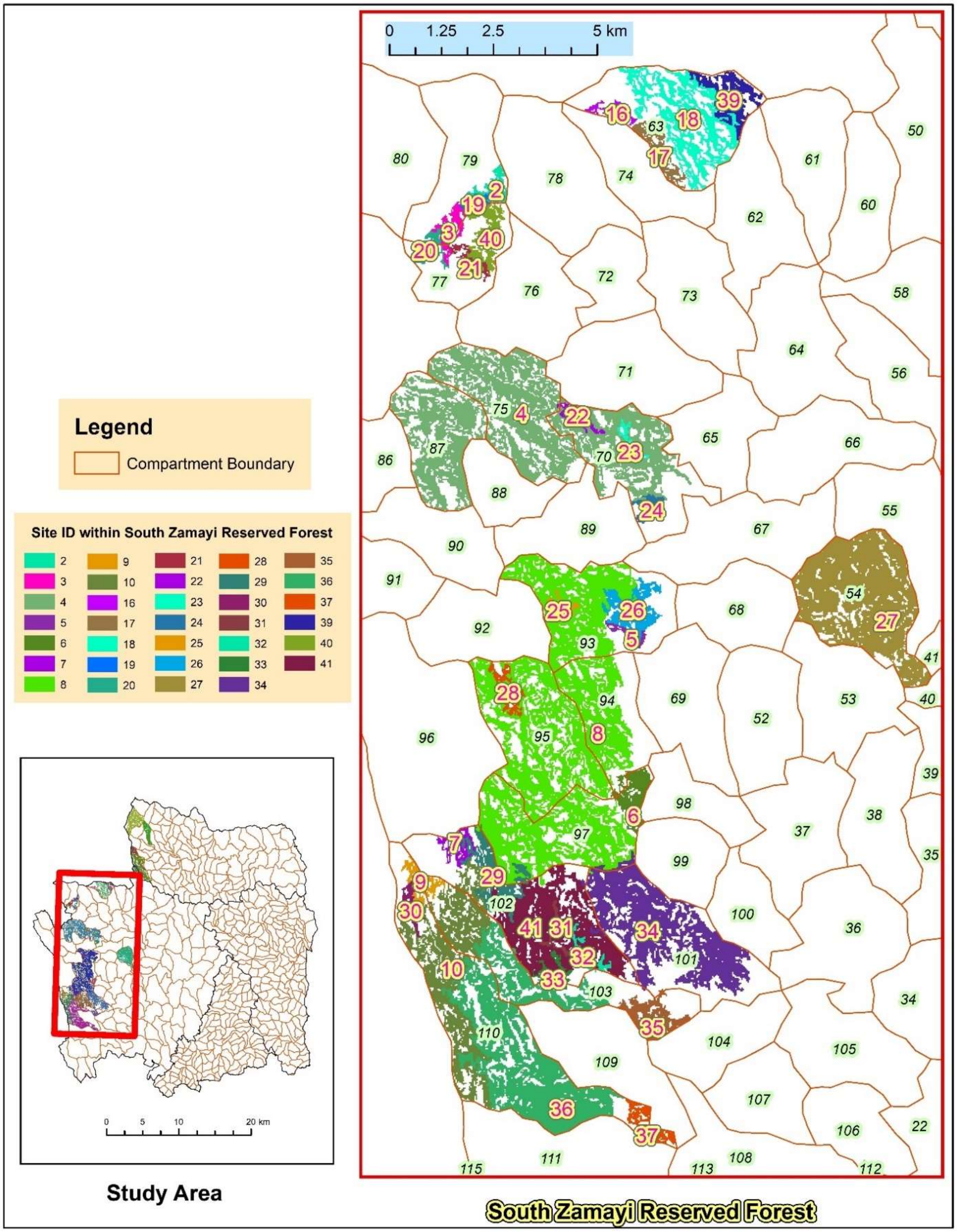


Figure 43. GIS-suggested sites with ID numbers for South Zamayi reserved forest. There is a total of 34 sites. Compartment numbers are also labeled.

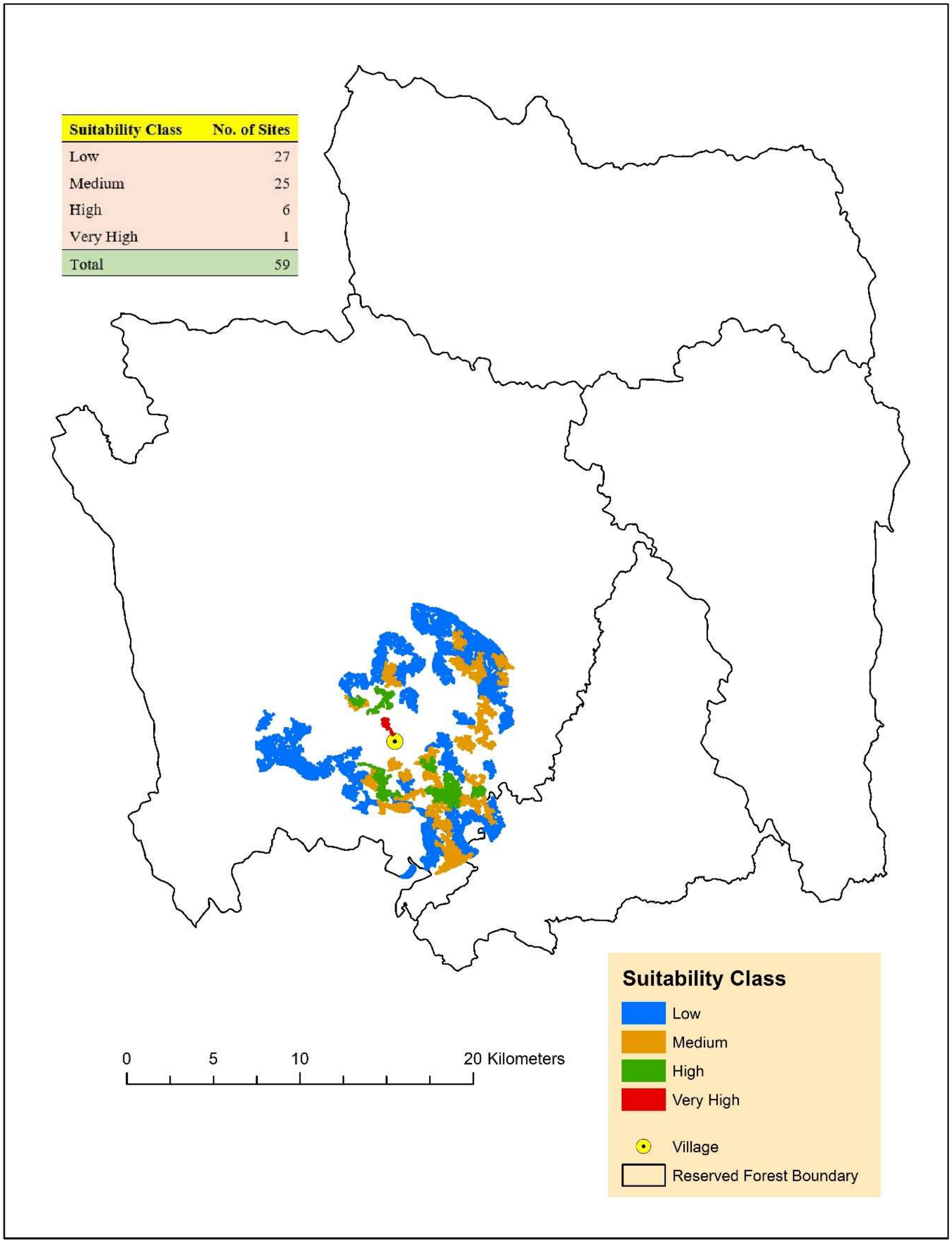
4.6. GIS Modeling- Sites for Community Forestry

Dawe was selected as the community forestry village. The selected village was originally part of the South Zamayi reserved forest area. In 2013, it was officially declared as village land. The households of the village served as the major labor source involved in the reforestation activities of the Forest Department. Hence, local people in the village were regarded as a suitable community for running the community forestry activities.

To determine possible areas for community forestry, five criteria were applied for the GIS modeling: land cover, slope, distance to roads, proximity to settlements and aspect. The sixth criterion, which was fulfilled outside the model builder, was a minimum size of 20 ha (about 50 acres). Like assisted natural regeneration, the integrated (i.e., rigid) GIS model, was employed. The GIS model suggested 59 sites (2.33% of the study area) for the implementation of community-based forestry. The 59 sites were designated into the following site suitability classes: 27-low, 25-medium, 6-high, 1-very high (Figure 44).

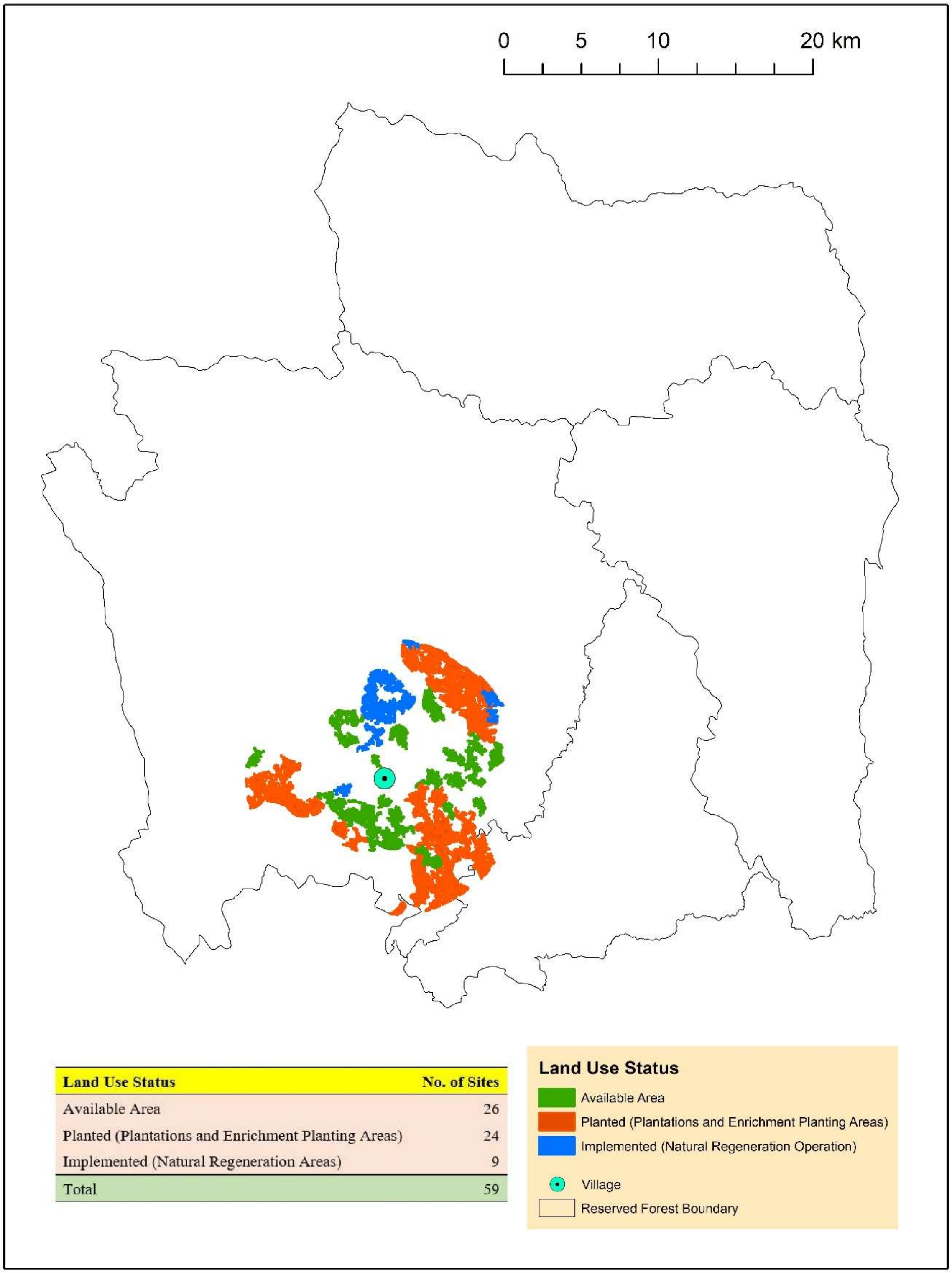
4.6.1. Availability of Land for GIS-suggested Sites

The sites obtained from the GIS model were cross-referenced with the existing land use data available at the local office of the Forest Department to determine the available land area. The review indicated that 24 sites had already been planted in the form of large-scale plantations and enrichment plantings. Also, 9 sites received assisted natural regeneration operations. In the end, 26 sites were recognized as viable for potential community forestry establishment, representing 44% of the initial proposed number (i.e., 59 sites) (Figure 45).



Suitability Class	No. of Sites
Low	27
Medium	25
High	6
Very High	1
Total	59

Figure 44. GIS-suggested sites with site suitability classes for community forestry. Potential community forestry areas were considered only within South Zamayi reserved forest.



Land Use Status	No. of Sites
Available Area	26
Planted (Plantations and Enrichment Planting Areas)	24
Implemented (Natural Regeneration Areas)	9
Total	59

Figure 45. Land Availability for community forestry. Proposed village means the village where community forestry users' group, who will manage the established community forest(s), lives.

4.6.2. Local Foresters' Re-ranking on GIS-based Suitability Classes

Among the available 26 sites (Figure 45), according to GIS-based site suitability classes, there were 12 sites ranked as low, 11 sites as medium, 2 sites as high and 1 site as very high. After further review by local foresters, the 26 sites were re-classified as follows: 13 sites as unsuitable, 1 site as low, 9 sites as medium, 2 sites as high and 1 site as very high (Figure 46 and Figure 47). They agreed with the most suitable (i.e., very high) site as the potential community forestry area. Like teak plantations and assisted natural regeneration, the land suitability classes defined by GIS modeling and foresters were compared by matrix format (Table 27).

Table 27. Matrix reporting the composition of site suitability classes between GIS-based and local foresters' classification for community forestry

GIS Suitability	Foresters' Suitability Classes					
Classes	Unsuitable	Low	Medium	High	Very High	Row Total
Low	7	1	3	1	0	12
Medium	6	0	5	0	0	11
High	0	0	1	1	0	2
Very High	0	0	0	0	1	1
Column Total	13	1	9	2	1	26

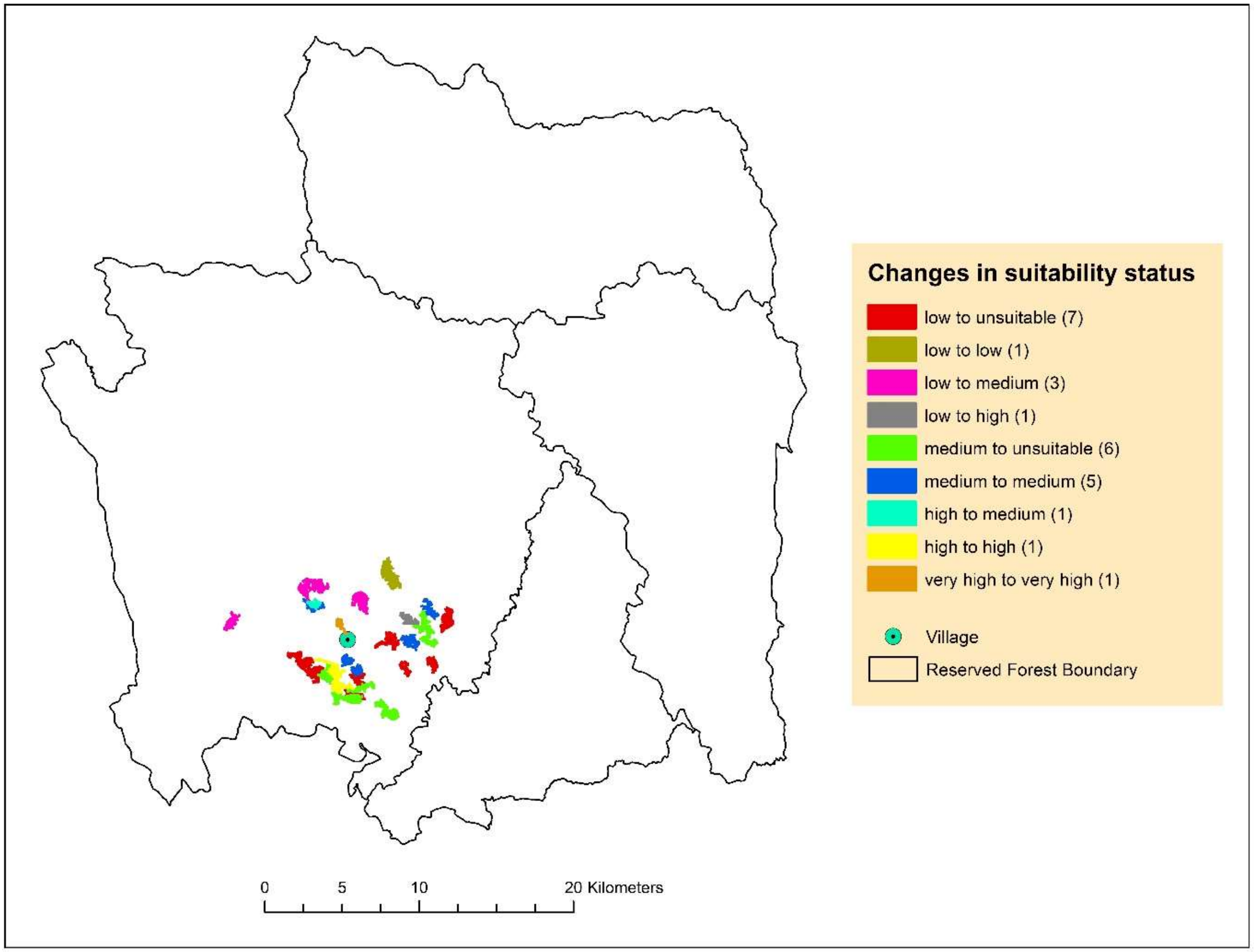
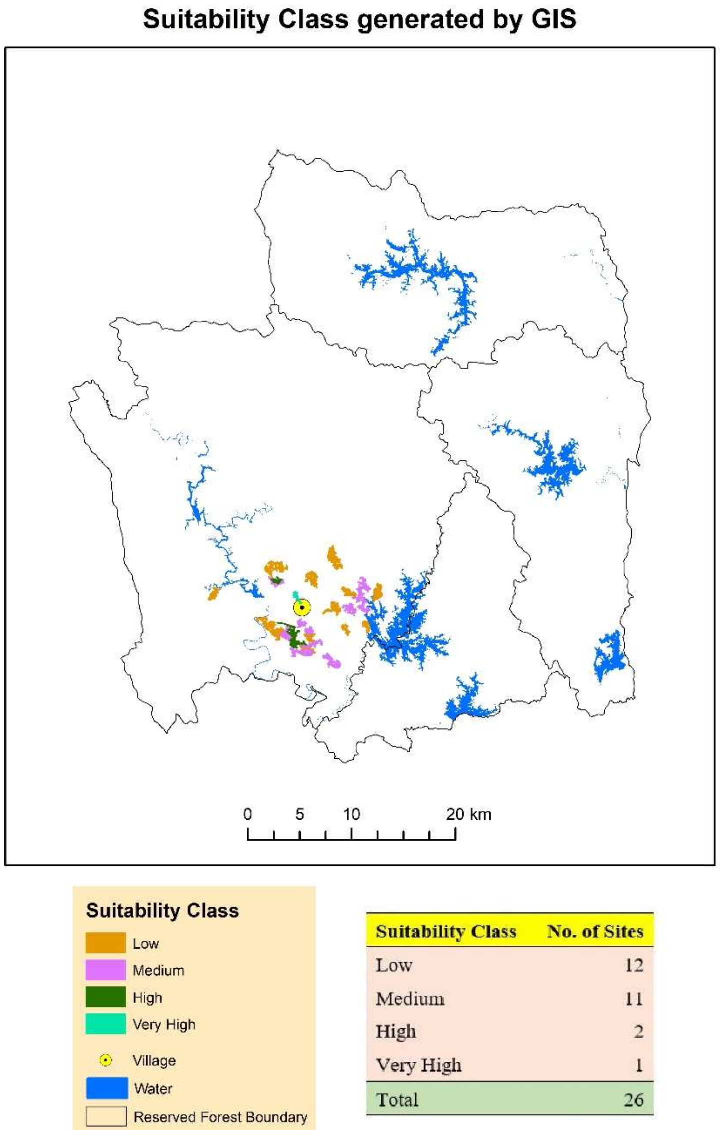
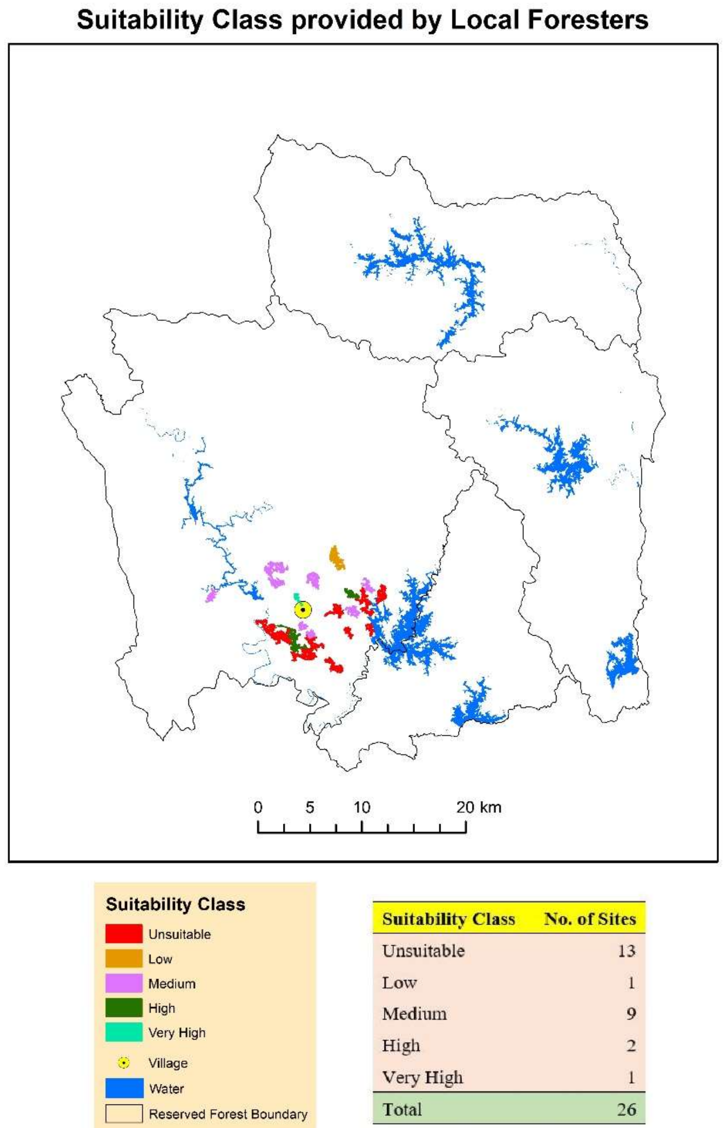


Figure 46. Map showing suitability class change status. The first suitability class was generated by GIS and the second (latter) one was provided (reclassified) by foresters. If the first and second classes are the same, it means that foresters agree with the GIS results. The numbers in the parentheses represent the total number of assisted natural regeneration sites. There are 26 sites in total.



Suitability Class	No. of Sites
Low	12
Medium	11
High	2
Very High	1
Total	26



Suitability Class	No. of Sites
Unsuitable	13
Low	1
Medium	9
High	2
Very High	1
Total	26

Figure 47. Site suitability classes for community forestry generated by GIS versus determined by local foresters

4.6.3. Justifications of Local Foresters on Customizing the GIS-based Site Suitability Classes for Community Forestry

Like the cases of potential teak plantation and assisted natural regeneration sites, a comparison between the GIS model and the foresters' reclassification is provided. According to foresters' reclassification, 22% of the GIS-generated sites (13 sites out of 59), although available, were placed under the unsuitable category, mainly due to the vicinity of established plantations. The justifications of experienced foresters are given in tabular form (Appendix C). As mentioned earlier (Figure 44), GIS generated 59 sites. A large-scale map locating all those sites with corresponding site IDs (Figure 48) is illustrated. Those site IDs are respectively linked with a justification table (Appendix C).

4.7. Combination of Proposed Sites for Teak Plantations, Community Forestry and Assisted Natural Regeneration

A map merging the proposed sites for teak plantations, community forestry and assisted natural regeneration was developed. During the initial stage, implemented sites were filtered out in accordance with the existing land use data. Afterwards, the comments of foresters were obtained. As a result, 9 sites for plantations and 13 sites for community forestry were re-classified as inappropriate, and thus those sites were removed in this finalized combined map. In the case of assisted natural regeneration, even though there was no site recognized as unsuitable, there was only one site which had been already implemented. Thus, that 1 site was eliminated while reporting the combined map. The summarized results to generate the combined map is shown in Table 28.

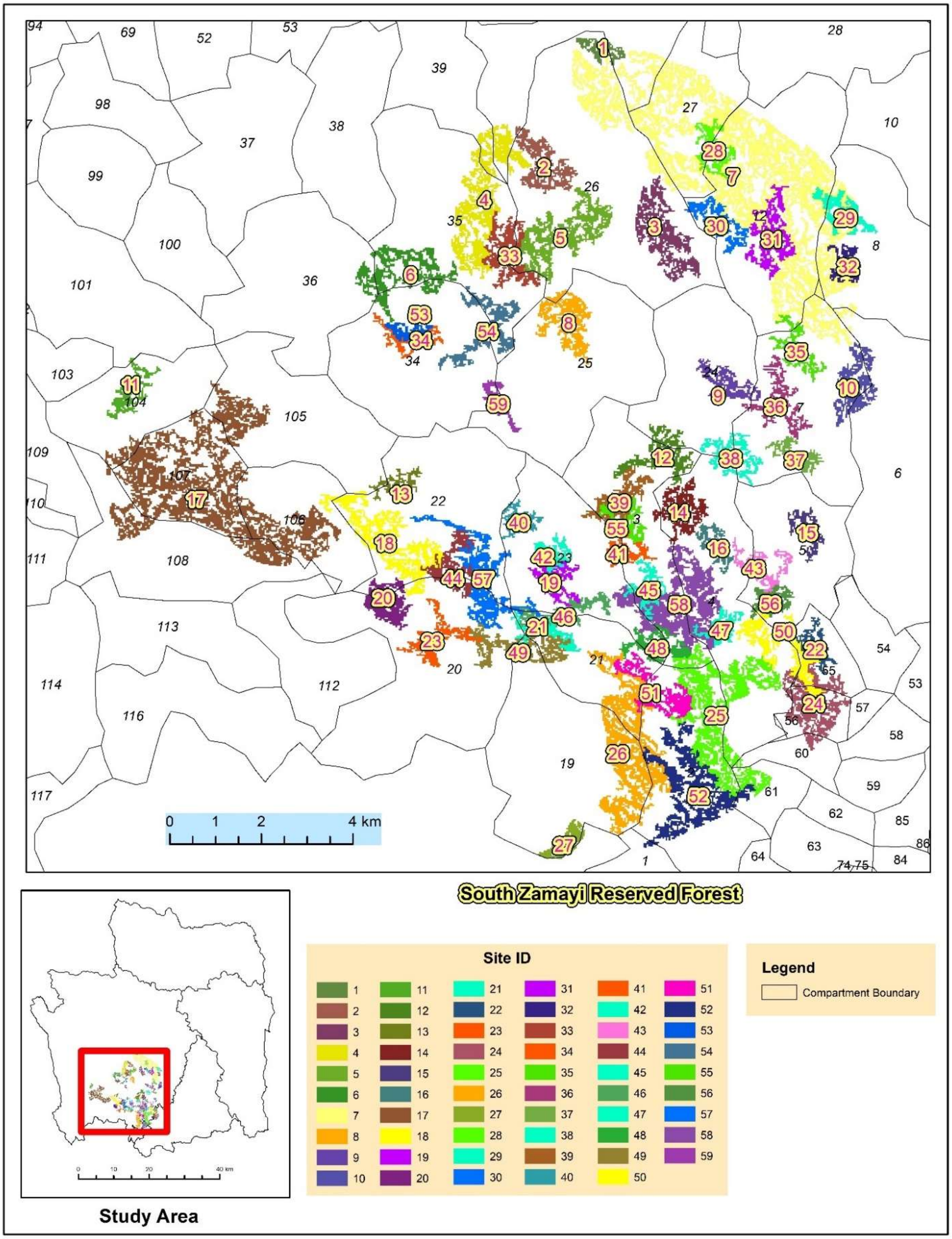


Figure 48. GIS-suggested sites with ID numbers. Compartment numbers are also provided.

Table 28. Summary of finalized available sites for the proposed reforestation activities

Operations	**GIS-suggested Sites**	**Already Implemented Sites**	**Available Sites**	**Unsuitable Sites**	**Final Candidate Sites**
Plantations	109	33	76	9	67
Natural Regeneration	41	1	40	0	40
Community Forestry	59	33	26	13	13
Total	**209**	**67**	**142**	**22**	**120**

4.7.1. Overlap Areas and Finalized Map

As expected, there were a few overlapping areas when all the finalized proposed forest management sites were integrated (Figure 49). There were two overlap areas between proposed plantation and assisted natural regeneration sites. In terms of site IDs, the overlaps were as follows: (1) between plantation site ID 19 (Figure 39) and natural regeneration site ID 35 (Figure 43), and (2) between plantation site ID 94 (Figure 36) and natural regeneration site ID 38 (Figure 42). In both cases, the two areas partially overlapped, and operational priority was given to the establishment of plantations.

In addition, there were five overlap areas between proposed plantation and community forestry sites. In terms of site IDs, the overlaps were as follows: (1) between plantation site ID 9 and community forestry site ID 65, (2) between plantation site ID 102 and community forestry site ID 38, (3) between plantation site ID 60 and community forestry site ID 3, (4) between plantation site ID 63 and community forestry site ID 6, and (5) between plantation site ID 66 and community forestry site ID 11 (Figure 39 and Figure 48). The first two almost completely overlap, and the other three partially overlap. The final decision was to give priority to the plantations (Figure 49).

There was no overlap between proposed community forestry and natural regeneration sites (Figure 49). As mentioned earlier, if proposed areas overlapped, priority was always for teak plantations (Figure 50).

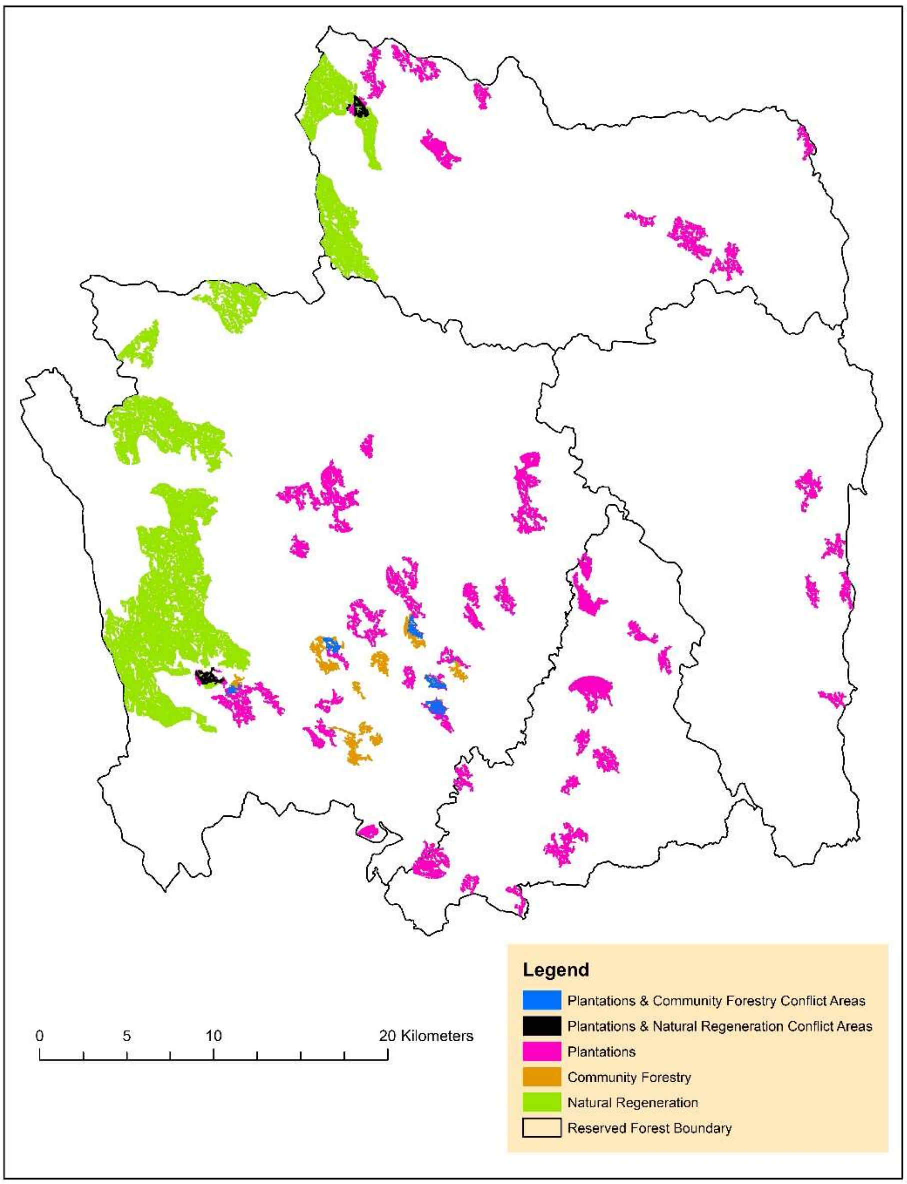


Figure 49. Map showing the overlap areas (1) between plantations & community forestry candidate sites and (2) between plantations & assisted natural regeneration candidate sites

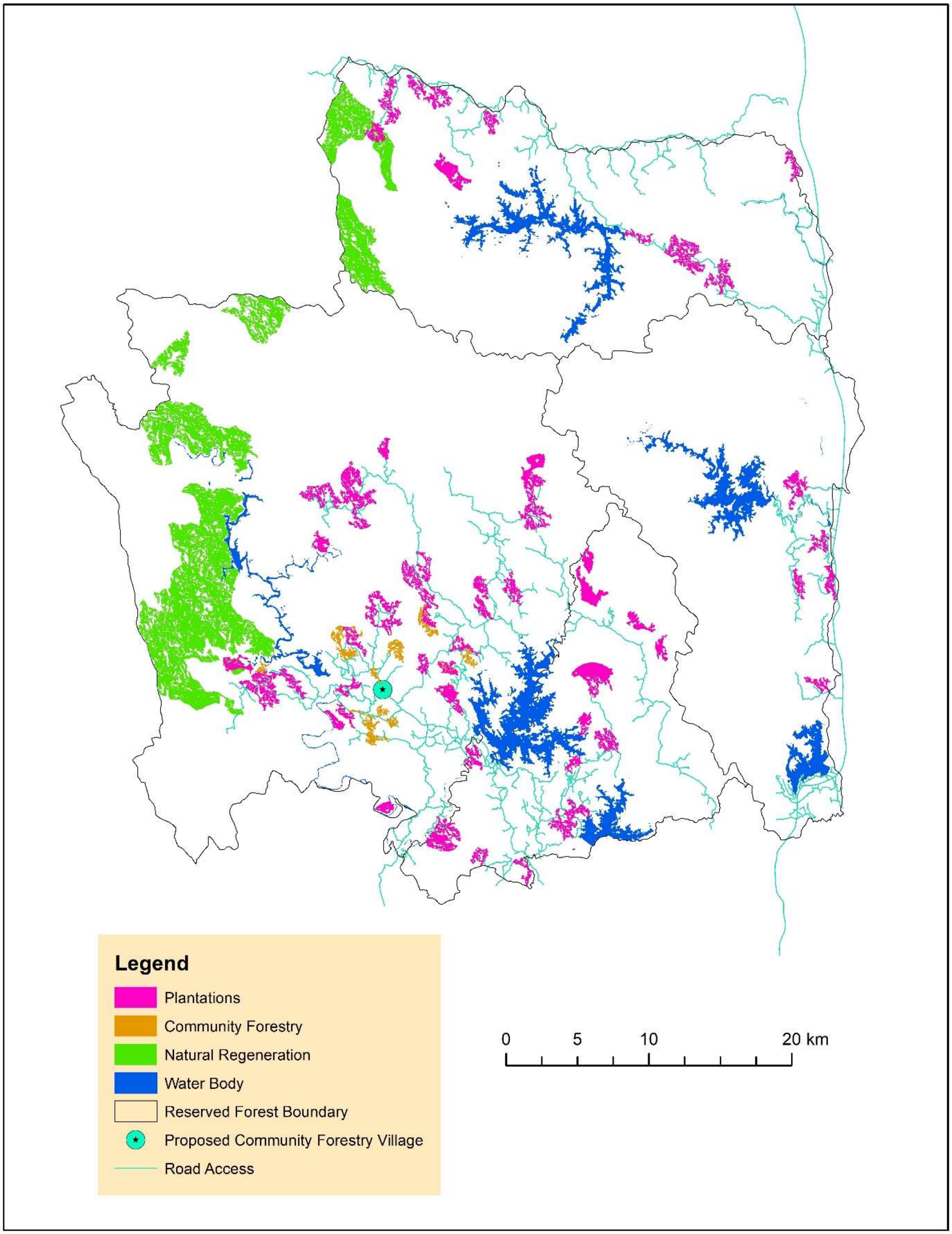


Figure 50. Final map showing candidate sites for respective reforestation activities

4.8. National Reforestation and Rehabilitation Program of the Forest Department

The Forest Department of Myanmar recently developed the Myanmar reforestation and rehabilitation program (MRRP) on August 30, 2016. The objective of the program is to restore the diminishing forest resources nationwide. One of the products from the MRRP was a 10-year (from 2017-2018 to 2026-2027) plan for the implementation of reforestation activities on a national scale. The results of this study were compared with the MRRP, despite the absence of GIS technology to determine site suitability. The comparison was limited to the study region.

The MRRP recommended 13 different reforestation initiatives: (1) agro-forestry, (2) economic plantations (commercial teak plantations), (3) private teak plantations, (4) private hardwood plantations, (5) recovering old plantations, (6) watershed plantations, (7) assisted natural regeneration, (8) community forestry, (9) pruning and cleaning, (10) seed production areas (SPA), (11) enrichment planting, (12) thinning and (13) fuelwood plantations. Within the study area, MRRP suggested 12 of the reforestation initiatives, with the exception of fuelwood plantations.

4.8.1. Categorizing the Reforestation Activities of MRRP

The 12 MRRP initiatives planned by the Forest Department were consolidated into either plantation, assisted natural regeneration, or community forestry to meet with the outline of this study. For instance, five operations representing agro-forestry, commercial teak plantations, private teak plantations, recovering old plantations and watershed plantations were classified as "plantations". The comparison between the locations of the five proposed MRRP plantations and the sites generated by this study indicate similar vicinities but not much direct overlap (Figure 51).

Assisted natural regeneration was kept under the "assisted natural regeneration" category in this comparison. Per the MRRP initiative, there are 20 proposed sites. The comparison between the MRRP plan and the result of this study indicate almost no overlap (Figure 52).

Community forestry was also put under "community forestry" category in this comparison. Per the MRRP, there was only one community forestry site suggested within Kawliya reserved forest while this study recommended a community forestry site within South Zamayi reserved forest (Figure 53).

The private hardwood plantation sites mentioned in the MRRP were not considered in this comparison because this study only focused on teak. In Myanmar, teak and hardwood are separately grouped. Thus, hardwood here refers to other valuable hardwood species but not teak.

Pruning and cleaning, seed production areas and thinning were MRRP operations suggested for established plantations – thus not related to this study. Therefore, those sites were not displayed in this comparison. Enrichment planting is a kind of planting, but it was not the intensive large-scale planting like plantations, and thus, such operational sites were not shown in this comparison.

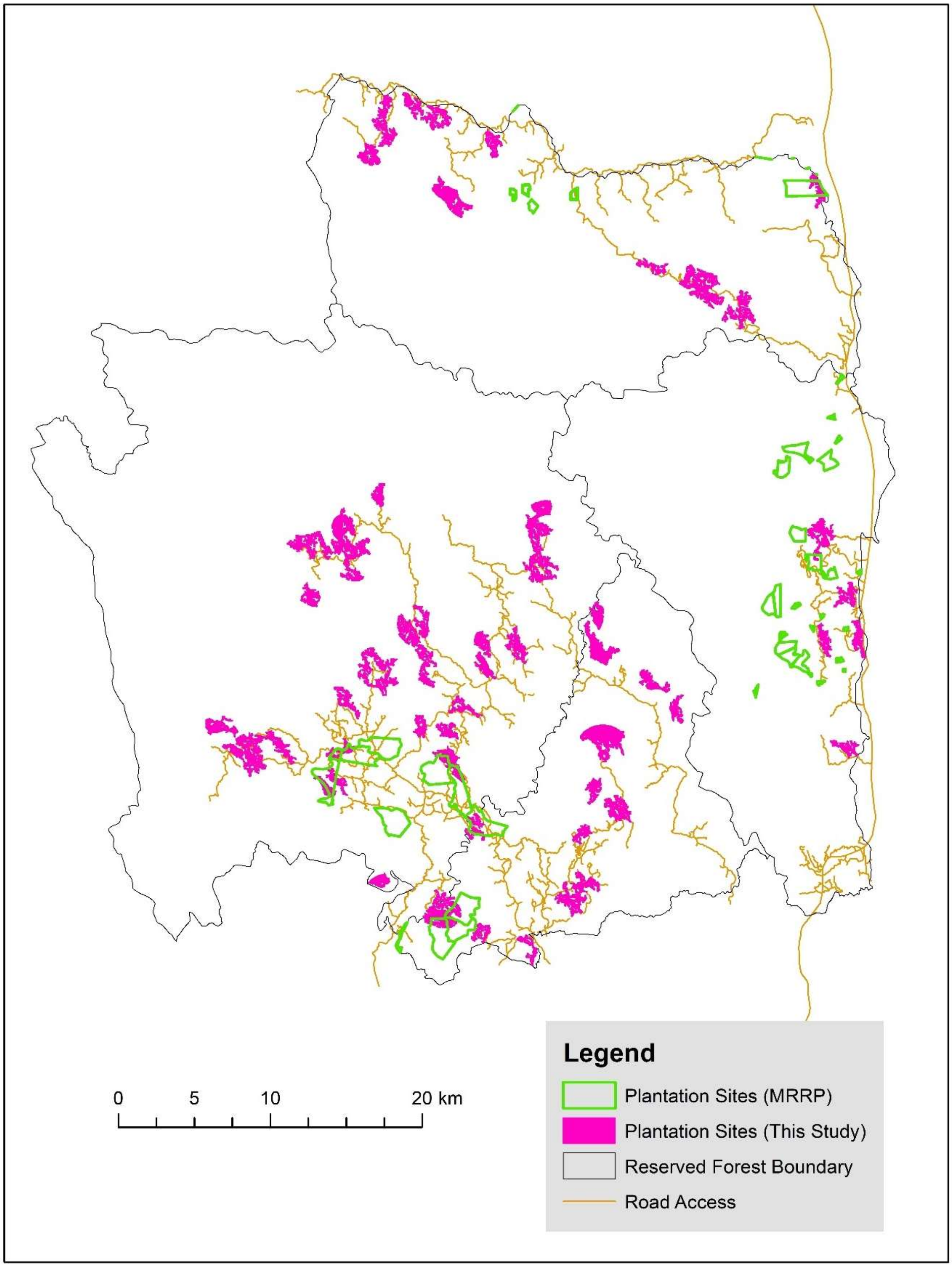


Figure 51. Comparison between plantation sites planned by the Forest Department and plantation sites recommended by this study. MRRP means Myanmar reforestation and rehabilitation program.

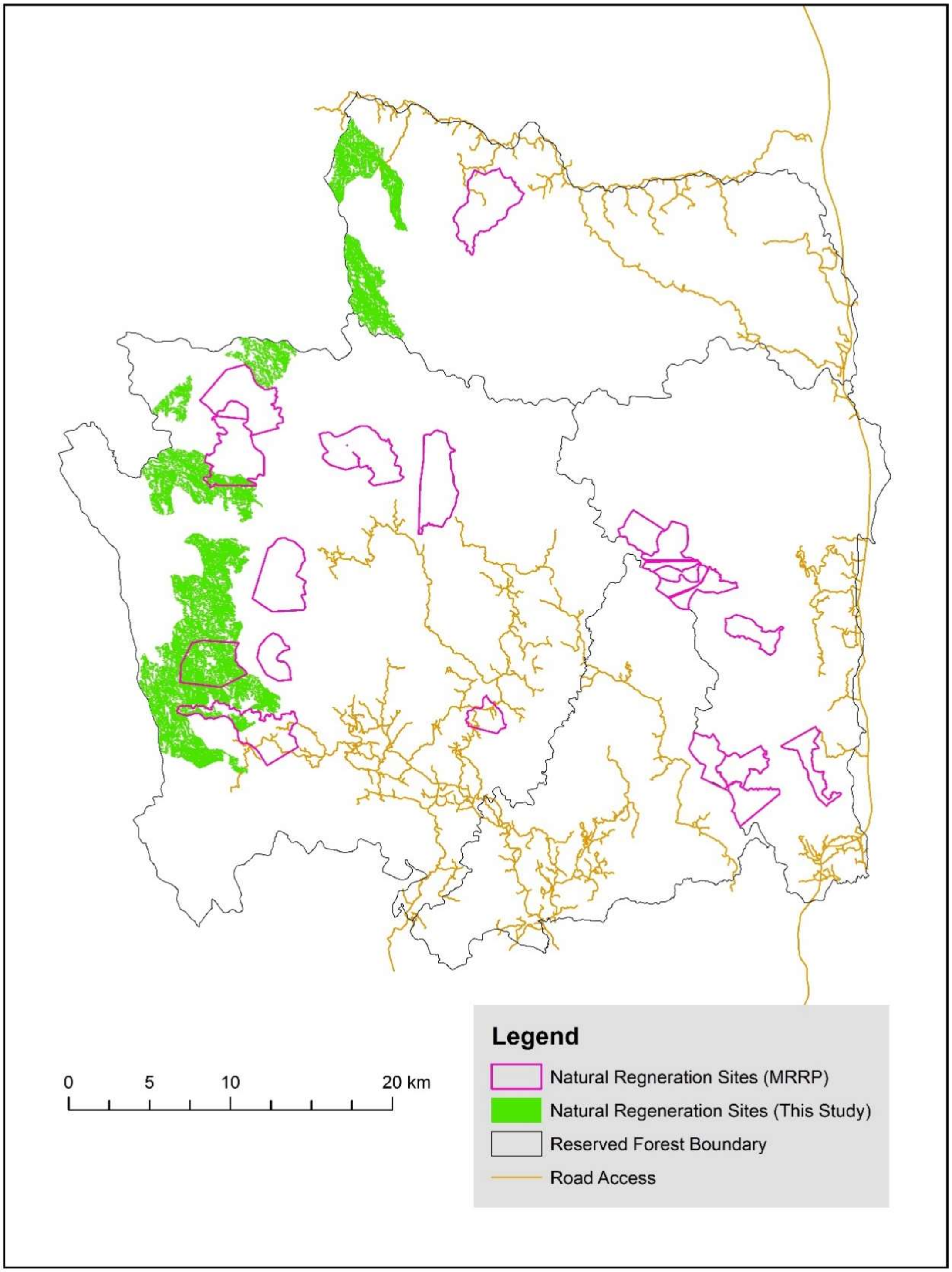


Figure 52. Comparison between assisted natural regeneration sites planned by the Forest Department and assisted natural regeneration sites recommended by this study. Even though MRRP planned to conduct assisted natural regeneration operations in Kawliya reserved forest, there was no teak logging within the past 10 years.

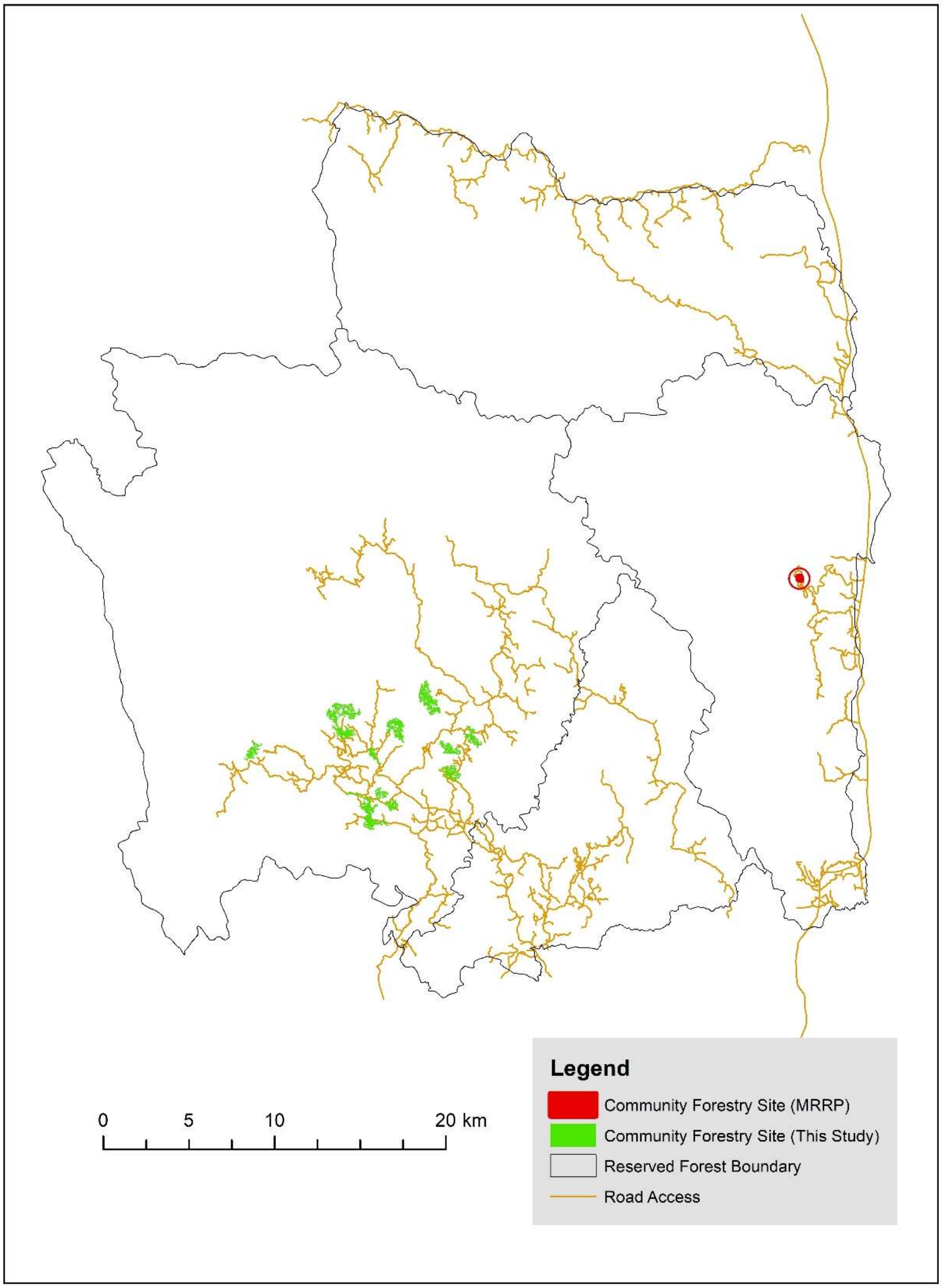


Figure 53. Comparison between community forestry sites planned by the Forest Department and community forestry sites recommended by this study. There was only one community forestry site in Kawliya reserved forest according to plan of the Forest Department. There were 13 sites suggested by this study in South Zamayi reserved forest.

CHAPTER 5
DISCUSSION

Historically being the "Home of Teak", the study site and relevant recommendations from this study should be of great interest to forest conservation groups. Reporting the rates of forest degradation was followed by GIS site suitability analyses to provide optimal site recommendations for teak restoration. Cross-referencing with the local Forest Department foresters and comparing the end results with the reforestation plan of the Forest Department confirmed the reliability of this study. This study provided a protocol to initiate reforestation efforts by reporting very important spatial information. This discussion chapter highlights and summarizes the interpretation of results, limitations, comparison and reference to other similar studies and implications for management.

5.1. Supervised Image Classification and Maximum Likelihood Algorithm

The initial focus of this study was generating land cover maps for 2000 and 2017. For the 2017 image, prior field work helped a lot in learning land cover types that would later contribute to more effective interpretation as training samples in supervised image classification. For the 2000 image, reliable historical data on the land cover types was lacking. Win et al. (2009) used the real-time image as the reference image to adjust the historical images during their forest cover change studies in the Bago Mountain region. In this study, the land cover types learned while classifying the 2017 image were used as a reference for the 2000 image. Consequently, there were limitations on interpreting the medium-resolution Landsat image which impacted the overall accuracy. As reported earlier, this study achieved 87% for the 2017 image and 83% for the 2000 image. Despite some debate, the overall accuracy of 85% is usually regarded as the target for thematic mapping from remote sensing imagery (Abeyta and Franklin 1998; Brown et al. 2000; Foody 2008; Ge et al. 2007; Treitz and Rogan 2004; Wright and Morrice 1997). If 85% was assumed as the target, the 2000 image classification required 2% of accuracy to meet with the standard.

Regarding the methods applied for land cover classification, Mon et al. (2010) used canopy density percentage as an indicator to classify forests. They considered forest canopy density (FCD) ≥ 70% as closed canopy forests, 40% ≤ FCD < 70% as medium canopy forests, and 10% ≤ FCD < 40% as open canopy forests. However, according to field observations, forest classification based on canopy cover percentage may be a poor approach in the study area due to the aggressive site occupation of bamboo species that can be confused with actual timber forests, especially during the visual interpretation of Landsat image. Thus, this study integrated ground referencing to help define training samples for supervised image classification. Other remote sensing data and techniques may be possible for mapping this homogenous vegetation structure e.g., using space-borne remote sensing radar data integrated with the visible and infra-red (VIR) images (Aschbacher et al. 1995), applying Green-Red Vegetation Index (GRVI) as a phenological indicator based on multiyear stand-level observations of spectral reflectance and phenology and classifying vegetation types (Motohka et al. 2010), linear mixture model which is applied to Amazonian vegetation classification (Lu et al. 2003).

The necessary steps of image classification may involve data acquisition, image pre-processing, selection of an appropriate classification method, training sample selection, post-classification processing, and accuracy assessment (Tuia et al. 2011). This study used a pixel-based supervised image classification method based on maximum likelihood algorithm to generate 2000 and 2017 land cover maps. Supervised classification consists of identifying spectral classes representing land cover features based on the known land cover types (i.e., training samples) (Jensen and Lulla 1987; Mon et al. 2012a).

Maximum likelihood classifier (MLC) is considered one of the commonly used algorithms for supervised image classification because it relies on statistical parameters (i.e., quantitatively examining both the variance and covariance of the spectral response patterns) when identifying the unknown pixels (Mon et al. 2012a; Shalaby and Tateishi 2007). Using three classification methods in the central Bago Mountains, Mon et al. (2012a) found that the MLC method, the standard method of image classification for supervised image classification (Xie et al. 2008), could give a higher accuracy than multiple linear regression method, but it was less accurate than the forest canopy density mapper method.

Nevertheless, Win et al. (2009) used MLC for supervised image classification in the Bago Mountain region. Lu and Weng (2007) assumed that MLC may be the most frequently used algorithm due to its good performance and accessibility in remote sensing software.

A variety of classifiers, such as parametric classifiers (e.g., MLC) and non-parametric classifiers (e.g., neural network, decision tree), have pros and cons (Franklin et al. 2003; Lu and Weng 2007; Tso and Mather 2001). On the condition that sufficient training samples that represent the authentic ground conditions can be provided and the data follow normal distribution, MLC can provide a satisfactory classification result (Lu and Weng 2007). In this study, with the support of ground reference, a total of 140 training samples (i.e., 27 samples for forest, 54 for degraded forest/ bamboo forest, 16 for other wooded land, 14 for other land and 29 for water body) were provided for the 2017 image. For the 2000 image, referring to 2017 land cover types and Google Earth, 123 training samples (i.e., 32 samples for forest, 15 for degraded forest, 12 for other wooded land, 32 for other land and 32 for water body) were fed into the ERDAS Imagine to run the supervised image classification.

5.2. Image Classification Accuracy Assessment

Stratified random sampling (i.e., the number of sample points are stratified to the distribution of thematic land cover classes) is regarded as an optimal sampling decision for this study because stratifying by land cover class based on the level of importance is a recommended practice to heighten the precision of the overall accuracy estimates (Stehman and Foody 2009). In other words, stratified random sampling is well suited for meeting the target of precisely estimating class-specific accuracy (Stehman and Foody 2009). The priority land cover types (i.e., forests, degraded forests and other wooded land) would later be used as GIS layers for site suitability analyses, although other less important land cover types were presented. Therefore, although the calculation steps were more complicated than simple random sampling, stratified random sampling was employed in this study.

There are some design options to evaluate accuracy such as a point, pixel, polygon, or other spatial elements, like 3 x 3 pixel block (Stehman and Foody 2009). This study used the point as a response design. As a good rule of thumb, a minimum of 50 sample points is advisable for each land use land cover category in the error matrix (Congalton 1991). Thus, this study generated a total of 310 points to estimate the classification accuracy: 50 points for less important land cover types and 70 points for priority land cover types. Stratified random points were created in the ArcMap platform and imported to the Google Earth Pro to assess the accuracy. Other comparable studies also applied point sampling for accuracy assessment. Mon et al. (2010) used a random sampling design, creating a total of 171 points in their forest canopy mapping studies. Furtuna et. al. (2016) used 100 random sample points to assess the accuracy of their change detection. This study used 310 stratified random points.

Training samples for image classification were provided to the software based on field inspection, which was completed before the commencement of the rainy season. However, for accuracy assessment, ground validation of all those sample points was practically infeasible due to limited road access and rainy weather. Thus, the accuracy assessment of this study employed high-resolution image freely available at Google Earth. Google Earth and other simulated global mapping systems are extensively employed for data collection and validation in remote sensing studies (Bhagwat et al. 2017; Gong et al. 2013; Gong et al. 2011; Yu and Gong 2012). Google Earth is particularly useful for collecting training or validation data where detailed field inspection is practically challenging, expensive and risky (Bhagwat et al. 2017). Ahmad et al. (2017) also relied on Google Earth maps as cross-validation in their agroforestry suitability analysis based on nutrient availability mapping. Furtuna et al. (2017) also manually labeled random sample points on high-resolution image available in Google Earth to assess accuracy. Bhagwat et al. (2017) also used Google Earth as a ground-truthing reference. The Forest Department of Myanmar relies on Google Earth as well to report accuracy assessment.

According to the assessment through 310 sample points, this study obtained 87% overall accuracy for the 2017 image and 83% for the 2000 image. Another similar study by Win et al. (2009) reported accuracy rates of 78.7% for 1989-2000 and 74.4% for 2000-2003 for classified maps as part of a forest cover change detection study in the Bago Mountains. Mon et al. (2010) studied three reserved forests in the core Bago Mountains and generated forest canopy density maps from Landsat images. They obtained 81% overall accuracy for 2006 images. This study achieved a little bit higher accuracy due to the prior field inspections that helped better understand the land cover types of the study area which was further reinforced by previous work experience in the region and supplementary land use data available from the Forest Department. In addition, the input provided by field foresters and satellite image experts from the GIS and remote sensing section of the Forest Department also accounted for achieving this level of accuracy.

Most of the classification studies only reported the overall accuracy and kappa coefficient. In this study, in addition to overall accuracy, the percent area, variance and standard error estimates were reported for the 2000 and 2017 classifications (Table 15, Table 16, Table 17 and Table 18), which are key components of statistical analysis when sampling the population. For the classified 2000 map, the overall standard error was 2.85. The classified 2017 map had an overall standard error of 2.5.

5.3. Detecting Changes in Forest Cover

Estimating the classification accuracies for each image was followed by presenting the area composition of respective land cover types in the study area. This study accounted for a 16-year period from December 2000 to January 2017. The areas classified as forest declined by 56% during 16-year period. Correspondingly, other land cover types increased as follows: degraded forests/ bamboo forests by 35%, other wooded land by 94%, other land by 198% and water bodies by 94%. This increase in water bodies was the result of four new dams between 2000 and 2017, which also contributed to deforestation in the study area. Win et al. (2009) reported that cutting before dam construction was the main factor in deforestation in the Bago Mountains. In addition, the dams and their associated access systems decreased forest cover due to the submersion of forested areas as well as illegal cutting due to improved accessibility. Another significant factor potentially influencing forest cover change was a highway road construction project between the two big cities of Yangon and Mandalay for the purpose of improved transportation. Furthermore, there was a significant amount of commercial timber extraction before 2016 (the logging ban year), which could contribute to forest cover changes.

In terms of changes, the annual deforestation (conversion from forest and degraded forest/ bamboo forest to other non-forest land cover types) rate was 0.78% and the annual rate of forest degradation (i.e., conversion from forest to degraded forest/ bamboo forest) was 1.35% revealing that the rate of forest degradation was higher than that of deforestation. In terms of area, this study found that the conversion from forest to degraded forest/ bamboo forest was the greatest (i.e., 38,090 ha). That finding was consistent with Mon et al. (2010) who estimated the change rate for three reserved forests in another part of the Bago Mountains. They found that the annual deforestation rate was 0.2% and the annual forest degradation rate was 2.5% between 1989 and 2006. They concurred that forest degradation was greater than deforestation, emphasizing that promoting desirable tree species composition was a priority. Given the rate of forest degradation, Win et al. (2009) also suggested more research on species composition, diversity, and successional forest structure following selective logging. However, Mon et al. (2012b) maintained that selective logging itself did not lead to either deforestation or forest degradation if the prescribed annual allowable cut was strictly maintained. Prior literature and this study suggest that degradation is threatening the sustainability of the Bago Mountain region no matter which study methods are applied.

5.4. Reforestation Options

In this study, three reforestation activities are proposed: teak plantations, assisted natural regeneration and community forestry. There is another operation namely, enrichment planting, commonly practiced by the Forest Department. It is a form of planting in recently harvested areas, and thus it is like teak plantation establishment. But an average of 70 trees per acre is planted for enrichment planting (Standard Operating Procedures 2016). It is fair to say that it is obviously not as extensive and intensive as commercial teak plantations because approximately 537 plants per acre (with a 9 ft spacing) are usually planted for teak plantations. Although enrichment planting sites were not recommended in this study, teak plantation sites can possibly be used as candidate sites for enrichment planting in case funding is a constraint according to the Forest Department foresters.

In bamboo-dominated degraded forests where natural regeneration is difficult (Khai et al. 2016), teak plantation establishment is the most practical option for rehabilitation. Thus, in this study, degraded forests/ bamboo forests and other wooded land (such as scrubland, bushes and completed shifting cultivation areas) were considered as potential areas for teak plantations during GIS modeling. Large-scale plantation forestry in Myanmar began in the early 1980s (Maung and Yamamoto 2008). The Forest Department is setting up plantation villages and employing taungya for teak plantations (Maung and Yamamoto 2008). The taungya (slash-and-burn) method is ideally used as site preparation for plantation establishment in bamboo-dominated forests. It is a one-strike-two-cuts approach: suppressing the domination of bamboo and in the meantime, increasing the composition of desirable teak species. Suzuki et al. (2004) also reported taungya teak reforestation as a successful example of tropical plantations. Maung and Yamamoto (2008) suggested that the Bago Mountain should be the main region for special teak plantation program.

Another possible option for reforestation of this study area is assisted natural regeneration. Assisted natural regeneration may range from improvement felling, thinning, pruning, climber cutting, coppicing, weeding, dispersing seeds and fire protection (Standard

Operating Procedures 2016). In addition to such operations, it is widely accepted that during bamboo flowering (i.e., bamboo dieback) is the best time for assisting teak regeneration because teak is shade intolerant. Although the longevity of bamboo varies with species, canopy opening occurs when bamboos flower. Bamboos die after flowering. Ideally, this is the best conditions for teak seedlings to grow very rapidly because they are free from bamboo suppression. The domination of the bamboo canopy retards the availability of sufficient light which is vital for the healthy growth of teak seedlings. Thein et al. (2007) reported that the coincidence of bamboo flowering and logging operations could significantly encourage height development of teak seedlings due to the open canopy. Quantitatively, they found that 84-96% of tree saplings overtopped bamboos in areas receiving logging operations and bamboo flowering, but it decreased to 53-56% in areas with no logging. Thus, in this study, most recently logged areas (i.e., between 2000 and 2014) were nominated for assisted natural regeneration because assisting the teak regeneration soon after logging is the best time for this proposed forest operation. As per Khai et al. (2016), regeneration is difficult for degraded forests where bamboos dominate. The advantage of assisted natural regeneration is that weather is not a critical challenge like teak plantations (which are intensively operated during rainy seasons) because natural regeneration operations are implemented during winter (dry) season. The study area has temporary logging roads, earth roads, seasonal forest roads for log transportation and village and dam access roads. The rainy season can range from the end of May to November and the average annual rainfall varies between 2,520 mm and 3,793 mm (per precipitation data collected between 2006 and 2015) (Bago District Working Plan 2016). As a consequence, during the rainy season, earth road access is an absolute challenge which can hinder the plantation operations.

Another advised reforestation activity was community forestry. To encourage community forestry development, the previous community forestry instructions, legislated in 1995, were customized in accordance with the current conditions and updated in 2016. Community Forestry Instructions (2016) encourage the community forestry role to expand from a subsistence to commercial level. Community Forestry means forestry operations in which the local community willingly participate in establishing new plantations and managing existing forests to generate job and income opportunities from a need-based to a more commercial scale (Community Forestry Instructions 2016). The local community can apply for a community forestry certificate, which is granted for a 30-year lease with the Forest Department. Such land ownership privilege is maintained as long as the rules described in the Community Forestry Instructions (2016) are not violated. In this study, a plantation village, where user group could be established, was selected as the community forestry village. According to Community Forestry Instructions (2016), user group means groups organized by households among the community who are interested in forest operations, living within 5 miles of the community forest for a consecutive five-year period and forest dependent people. In this study, to encourage the participation of local people, potential community sites were recommended based on the community forestry instructions, bio-physical factors and opinions of the Forest Department.

5.5. GIS Modeling and Weighted Overlay Analysis

Geospatial tools for determining plantation establishment are increasingly applied by many authors (Aguirre-Salado et al. 2015; Delgado et al. 2010; Falasca et al. 2012; Gallegos et al. 2007). There were prior researches using different remote sensing techniques (such as canopy density mapper, multiple linear regression, normalized difference vegetation index (NDVI) image differencing, etc.) to evaluate the status of forests. However, to my knowledge, there is a scarcity of published research in determining suitable areas for reforestation in the Bago Mountain region using geo-spatial analysis. As a result, most references were supported by research outside Myanmar. That heightened the question of whether the results of this geospatial analysis were satisfactorily applicable for determining suitable forest management options in the Bago Mountain region of Myanmar.

Overlay is widely applied to suitability analysis and raster overlay is particularly recommended (Price 2016). With respect to discussion about the methods applied, between the Boolean overlay and weighted overlay, the latter was used in this study because the weighted overlay can provide a more flexible and sophisticated approach to suitability modeling than the Boolean overlay (Price 2016). Boolean overlay considers all input layers as equally important, but that is not usually the ideal case in practice. Weighted overlay is designed to interpret more desirable factors, resulting in higher values for the output raster, and thus provides site suitability scores (Esri, 2016). The main drawback of weighted overlay is that assigning the suitability ranks and weights usually rely on the researcher's perspectives. Thus, prior knowledge about the study area is important to justify the weights. Despite its subjectivity, weighted overlay analysis is widely used for land suitability analyses in different geographical regions (Ahmad et al. 2017; Jaimes et al. 2012; Kar and Hodgson 2008; Li and Nigh 2011; Muñoz-Flores et al. 2017; Webb and Thiha 2002; Widiatmaka 2016).

Like other comparable studies, the model builder was used for the overlay analysis. GIS models can provide many advantages such as recording the steps and parameters used for the analysis which simplifies revision of the methodology if needed (Price 2016). In addition, models can be applied to determine the results of different parameters on the final outcome (Price 2016). That is a huge advantage for sensitivity analysis because in GIS multi-criteria decision-making methods, sensitivity analysis helps to understand the behavior of the model and its limitations (Chen et al. 2010).

In this study, as an alternative approach, although the title of study is weighted overlay analysis, weighted overlay tool was not employed during the analysis due to its default rounded function (i.e., integer values) rather than decimal values. However, it is possible to rescale the input values by multiplying the values by 10 or 100. Instead, the raster calculator tool was mainly used because it was found useful to maintain more precise decimal values in this study. Although the use of this alternative tool was not novel, it could offer more precise values that overrode the performance of the conventional weighted overlay tool. The innovation of this rigid GIS modeling was that the final answer was obtained by combining the weighted overlay (conventional way) and non-weighted overlay (which was simply to make sure eradication of unsuitable sites).

Therefore, the end results were typically not the zones mentioning the site suitability status. Preferably, this method offered more precise spatial information although it did not thoroughly cover the study area. However, as it recommended only the most suitable sites, its reliability was consequently improved. On the other hand, some may challenge the end results because this rigid analysis recommended only small proportions of the study area e.g., 4.41% of the study area for teak plantations, 4.75% for assisted natural regeneration and 2.33% for community forestry. In total, only 11.49% of the study area was recommended for reforestation activities because at least one input value was 0 in the rest of the study area. Despite limited area coverage, the rigid model has a huge advantage of suggesting the most qualified sites for individual reforestation activities. No further analysis is required because the resultant sites are precise and handy for practical implications, especially compared to the flexible GIS model.

Similar studies (Aguirre-Salado et al. 2015) found that over 80% of the area was suitable for commercial tree plantations with land suitability indices according to their spatial modeling multi-criteria/ multi-objective approach. Ahmad and Goparaju (2016) identified potential areas for urban forestry using parameters such as soil moisture, slope, soil organic carbon, drainage and urban buffers. They applied weighted mean for evaluating suitable sites and found that 27% of their study area as highly suitable, 38% as medium suitable and 35% as least suitable. Webb and Thiha (2002) used GIS for evaluating suitable forestry plantations using traditional and integrated methods. In the traditional method, they relied on biophysical suitability factors and found that 19.2% of their study area was suitable for plantations. In the integrated method, they considered both biophysical and socio-economic suitability factors and stated that 18% of the area was found suitable. But the resultant maps between traditional and integrated methods were spatially dissimilar to each other.

As stated earlier, the study area provides excellent habitat for teak growth and it would seem that the results of this study should recommend most parts of the study area. It should be noted that with the flexible modeling approach the suitable sites for teak plantations could be up to 95% of the study area (Figure 28). Nevertheless, the rigid approach of this analysis competitively selected only the most qualified sites, although its suggested coverage was not thoroughly distributed throughout the study area. To reiterate, the results of rigid (or integrated) model determined that 4.41% of the study area was suitable for teak plantations, 4.75% for assisted natural regeneration and 2.33% for community forestry.

5.6. Experts' Validation upon GIS-modeled Results

One of the good points of this study was that the GIS results were validated by expert opinion and available data sources. It was good to interview field staff who were well-experienced about the field conditions and land use status of their respective reserved forests. Confirming office data ensured the quality of research output. It was assumed that the opinions of foresters on suitable/ unsuitable modeling decisions reflected authentic field situations. However, similar to weight assignments for GIS suitability analyses, their ranking on land suitability classes seemed to be subjective. In other words, the results of GIS quantitative analysis were assessed with the qualitative interviews from the forestry experts.

In the case of GIS-modeled teak plantations, among the proposed 109 sites, 33 sites had already been planted according to the data available at the Forest Department and 9 sites were determined as unsuitable by local foresters. In the end, 67 sites with suitability indices were available for teak plantation establishment. Also counting the already planted areas, it can be stated that 92% of the GIS-modeled sites were suitable to local Forest Department foresters, although there were modifications on site suitability classes. Foresters' reasons for unsuitability were mainly due to proximity to reservoirs that might affect the core watershed area, and one site which almost overlapped with the existing established plantations. Why were existing plantations not eliminated prior to GIS modeling? Although desirable, it was impossible to remove those areas in advance because land use data were not archived in the form of GIS files during the data acquisition period. Almost all the maps showing the plantation sites and other land use data were recorded on paper and some of the sites had to be double checked with senior field staff, especially for plantations and forest operations established a long time ago. In addition, it was challenging to digitize all those plantations and land use data then convert into GIS format during the constrained study period. In the future, it is highly suggested for the Forest Department and future researchers to archive the map data and other widely used data in readily obtainable digital format for improved access.

In the case of assisted natural regeneration, the GIS model determined 41 sites as suitable. Foresters agreed with the results of the GIS model. In other words, 100% of the GIS-modeled sites were agreed as suitable, although changes on site suitability classes were added. Among 41 sites, only 1 site has been naturally regenerated. So, there are 40 additional sites available for implementation. This high level of agreement was achieved mainly due to following the existing standard operating procedures prescribed by the Forest Department. Assisted natural regeneration to create conditions for young advanced growth in the area was highly advisable in logged remote areas. The other probable reason of obtaining this high level of agreement is that natural regeneration is implemented during the winter (dry) season. Thus, accessibility is not as challenging as plantation establishment (which is implemented during the rainy season and constant care is needed for success). So, working conditions for natural regeneration are not that demanding in terms of budget and work load.

Regarding community forestry, the village of Dawe, which usually provided plantation labor source, was selected as the community forestry village. There is another village, namely Ma Doc Myaung, located nearby Dawe (Figure 12), but only one village was selected in this study. The reason for selecting only one village was that the other villages (such as Ma Doc Myaung, Phao and Nyar Tae) have already been given the right to manage a community forestry plantation in their vicinity. The selected village has yet to be offered the right to manage the community forestry. In addition, the Department foresters are very cautious about transferring the forest land to the local community because if such right is given, the lease will last for 30 years. If community forestry is located close to existing or new plantations of the Forest Department or private plantations, potential conflicts of land ownership might arise. That makes the expansion of community forestry development slow even though authentic people participation is always desired. Thus, it was found that although land area was available, Department foresters strictly scrutinized the GIS-modeled sites not only from an environmental standpoint but also from social and administrative perspectives.

The GIS model evaluated 59 sites for community forestry. Among them, 33 sites had been implemented in the field and 13 sites were considered as unsuitable by the Department foresters. Thus, 13 sites were available for initiating community forestry. Consequently, it could be deduced that the foresters agreed with 78% of the modeled sites. The remaining 22% of the GIS-modeled sites, although available, were unsuitable, mainly due to being in the vicinity of established plantations. Hence, according to research standpoint, the results delivered may not seem impressive, not because of unfavorable site (i.e., ecological) conditions, but because of administration-influenced rigid perspectives. As discussed earlier, acquiring and compiling the established plantation sites was not possible during the study period due to the Forest Department's data storage (i.e., paper-based) system and limited study time to digitize and archive considerable land use data. On the other hand, according to previous community forestry certification records, very few community forestry areas were usually given to a community forestry village. This study recommended 13 sites for community forestry, with a minimum area of 20 ha (50 acres). Thus, in practice, the number of sites suggested by this study was more than sufficient for the practical implications. Since the criteria defined for community forestry (Table 13) were almost the same with the criteria for teak plantations, remaining sites (after the final selection of one or more community forestry sites) could be transferred or integrated into the sites' plan for teak plantation establishment.

All in all, as per the cross-validation with the experts, it was found that this weighted overlay analysis of different GIS layers inputs such as land cover, biophysical factors, accessibility, logging records (in other words, the results of this GIS model) could convey satisfactory spatial information about vital reforestation hotspots. Subsequently, the results of this study will contribute to a long-term plan for teak restoration.

It will be better if this integrated GIS-based spatial analysis can be used for a larger region, up to national scale because of Myanmar's national deforestation issues. To scale up the research, additional data may be required such as soil, water, geological information, population count and density, agriculture, urban or impervious surface areas. Although a national reforestation plan has been developed, the planning process relies on the conventional way (i.e., reports sourced from the township level).

5.7. Comparing with Myanmar Reforestation and Rehabilitation Program (MRRP)

To combat deforestation, in 2016, the Forest Department developed a 10- year plan, known as the Myanmar Reforestation and Rehabilitation Program (MRRP). The results of this study were compared with results of the MRRP. The MRRP maps for individual operation sites were documented in GIS files. One reason for comparing this study with the MRRP was that there were some disparities in methodology between this study and the MRRP. Different approaches may give dissimilar spatial results. That assumption made this comparison interesting for reviews and possible revisions for both methods. The first difference between MRRP and this study was that MRRP did not apply geospatial technology to provide spatial information, allowing the opportunity to contrast traditional methods with more technical geospatial analysis. The second difference was that MRRP maintained close adherence to the objectives of working circles (Table 7). According to working circle guidelines, large-scale plantations are not recommended in the production working circle which focuses logging. However, due to the 10-

logging ban legislation in the study area, the production working circle should also be considered for reforestation activities (such as plantations) rather than logging.

This study selected four reserved forests within three townships of the Bago district. Literally, MRRP considered reforestation activities based on township administrative boundaries. However, this study considered reforestation activities based on reserved forests' boundaries regardless of three different townships. So, activities proposed in this study were limited to the boundary of selected reserved forests only. Nevertheless, MRRP considered beyond this study area (i.e., townships have more than one reserved forests) and thus, the MRRP could be impacted by the available reserved forests in individual townships. For example, Daik-U township has a limited number of reserved forests and thus, proposed activities might be busy in only one reserved forest. If there are a great number of reserved forests (e.g., Bago Township), reforestation activities may be fairly distributed among many reserved forests.

Figure 51 is the comparison map for plantation sites between this study and MRRP. The plantation sites nearly overlap or are close to each other for South Zamayi and Shwe Laung Ko Du Gwe reserved forests. As per the MRRP, there are only a few sites proposed for plantations in Shwe Laung Ko Du Gwe. In Baing Dar, there are not so many sites proposed by MRRP. Only one site overlapped with this study. According to the interviews with Department foresters from Kyauktaga township, MRRP considered other reserved forests (which are outside this study area) for plantations rather than Baing Dar.

The most striking scenario occurred in the Kawliya reserved forest. Kawliya is situated within the Daik-U township which has only four reserved forests: two reserved forests falling within Daik-U township and the other two (only small area) shared by neighboring townships (i.e., Bago and Kyauktaga). As a result, MRRP's proposed plantation sites for Daik-U township highly concentrated in Kawliya only and those sites are far away from accessible roads (Figure 51). As per confirmation with local Department foresters, road access during the rainy season can be a limitation even though a waterway may be a possible alternative. This study did not recommend those distant areas for candidate sites. Thus, major differences between MRRP and this study occurred in the Kawliya regarding plantation sites.

Figure 52 is the comparison map for assisted natural regeneration sites between this study and MRRP. Similar to the plantation sites, major differences occurred in the Kawliya reserved forest. The MRRP selected assisted natural regeneration sites which are a long distance from accessible roads. The reason for this is that MRRP strictly adheres to production or watershed working circles for assisted natural regeneration. This study did not follow the objectives of working circles; consequently, assisted natural regeneration areas were proposed only in areas logged within the last five years. No commercial teak logging was done in Kawliya in the past 10 years, resulting in the absence of natural regeneration sites in Kawliya in this study. As shown in Figure 52, the majority of comparable results are found in South Zamayi. Like the plantations scenario, MRRP considered other reserved forests rather than Baing Dar for Kyauktaga township. Therefore, only one site is proposed for natural regeneration in MRRP.

For community forestry, the MRRP selected only one site located in Kawliya reserved forest (Figure 53). However, the community forestry village does not exist within the reserved forest. It is assumed that the proposed village exists within 5 miles of the proposed community forest (Community Forestry Instructions 2016). Generally, the farther the distance, the less people participate in reforestation (Hlaing and Inoue 2013). Furthermore, the walking time is suggested to be a maximum of 2 hours (Hlaing and Inoue 2013; Poteete and Ostrom 2004). The participation of community forestry user group members in reforestation activities (such as meeting attendance, planting trees) may be somewhat impacted if walking distance is too far (Hlaing and Inoue 2013; Poteete and Ostrom 2004).

It has already been justified that due to a lack of a village inside the Kawliya, this study did not consider in determining potential community forestry in Kawliya although MRRP did. This study selected the potential community forestry village situated within the selected reserved forest (i.e., South Zamayi). In South Zamayi, there is a plantation village where settlements are well-experienced about forestry activities. This study proposed the community forestry sites nearby that village considering the above-mentioned physical factors. The obvious difference between this study and MRRP is not only the village location but also the number of recommended sites for community forestry (Figure 53).

Future Research

Advanced Remote Sensing Analysis

It was found that the results of forest cover change were generally consistent with the previous studies (i.e., deforestation and degradation). However, the actual figures reported had some discrepancies. This may be due to the methodologies applied or some other reasons. The unique feature of this study area was the domination of bamboo forests, although bamboo species are ecologically associated with teak. Subsequently, actual timber trees can be confused with bamboos, particularly during visual interpretation of medium-resolution Landsat image. Advanced remote sensing technology which can distinguish between trees and bamboos is recommended for further studies. Acquiring the remote sensing data that cover the visible and infra-red (VIR) spectrum up to the microwave region of the electromagnetic spectrum may help for vegetation mapping (Aschbacher et al. 1995). Applying Green-Red Vegetation Index (GRVI) as a phenological indicator and understanding the phenological response to meteorological conditions and classifying vegetation types may be helpful (Motohka et al. 2010). Linear mixture model which was employed to Amazonian vegetation classification may probably be an option as well (Lu et al. 2003).

Realistic Forest Classification Research

According to field observations, forest classification relying on canopy cover percentage may not be an effective approach in the study area. Due to the dominance of bamboo species, a more realistic and meaningful forest classification should be based on local conditions.

CHAPTER 6

CONCLUSION

Loss of forest cover in the teak-bearing forests of the Bago Mountains called for this spatial analysis research. Land cover maps for 2000 and 2017 were developed to document recent land cover changes. This study obtained overall accuracy of 83% for the 2000 classified map and 87% for the 2017 classified map. Through change detection analysis, deforestation and forest degradation were quantified. The next step was to provide spatial maps for forest restoration projects based on the ecological requirements of teak. These general goals are supported by the following study objectives:

Objective 1: To quantify forest cover changes and describe the rates of deforestation and forest degradation between 2000 and 2017.

According to forest cover change detection analysis between December 2000 and January 2017, it was found that the annual deforestation rate was 0.78%, and the annual forest degradation rate was 1.35%. These amounts of change rates implied that there was a 56% decline in forests and a corresponding 35% increase in degraded forest/ bamboo forest. The expansion of degraded forests sheds light on the decline of forests in terms of both quantity and quality.

Objective 2: To locate proposed sites for teak plantations, assisted natural regeneration, and community forestry based on the environmental requirements of teak and practical implications.

According to rigid (integrated) GIS modeling, this study identified 109 sites suitable for teak plantations, 41 sites for assisted natural regeneration and 59 sites for community forestry with land suitability classes. In other words, this GIS modeling recommended 4.41% of the study area for teak plantations, 4.75% for assisted natural regeneration and 2.33% for community forestry. In total, 11.49% of the study area was found suitable for three different reforestation activities.

On the other hand, the flexible GIS modeling revealed that 95% of the study area was found suitable for teak plantations and its results were illustrated in terms of land suitability zoning format.

Objective 3: To confirm GIS-modeled sites with the local Forest Department to assess its feasibility and accuracy.

According to experts' opinions on the results of spatial analysis, 92% of modeled plantation sites, 100% of modeled assisted natural regeneration sites, and 78% of modeled community forestry sites were evaluated as suitable, although there were modifications on suitability classes for some sites.

This study is an example verifying that development in geospatial technology such as open source satellite image processing and GIS suitability mapping can offer meaningful solutions for reforestation initiatives. Forest cover change figures resulting from this study confirmed that the continuation of forest loss is threatening the sustainability of forested areas in the Bago Mountains. If these ongoing undesirable trends cannot be reversed or controlled, the "Home of Teak" will be severely diminished in the future. The challenges of accelerated forest degradation should not be underestimated as its rate was apparently much higher than deforestation rate. Although different methodologies were developed to illustrate the tragedy of this historic area, there was a paucity of action-oriented studies (or at least no comparable published research) conducted to ameliorate this undesirable scenario. The research providing the practically actionable information with the help of cost-effective technology should be advanced.

The end results generated from this study can be used as a reference for reviewing the existing reforestation plan of the Forest Department. Furthermore, the recommended sites for teak restoration through this study could provide useful information for those who would like to invest in reforestation activities in the study area. The steps applied in this study can be advanced or integrated into the traditional site selection methods to achieve more cost-effective and reliable spatial information in a timely fashion.

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APPENDICES A – C

Appendix A. Comparison of suitability classes for teak plantations generated by GIS modeling versus defined by foresters

Table 29. Justifications of local foresters on modifying the GIS-based suitability classes for candidate teak plantation sites. Site IDs are linked with Figure 36, Figure 37, Figure 38 and Figure 39 which display the locations of each site. The GIS suitability classes and foresters' suitability classes are shown in comparison. The reserved forest and compartment number of each site are also reported. BD means Baing Dar, KY means Kawliya, SL means Shwe Laung Ko Du Gwe and SZa means South Zamayi. The remark/ justification column provides the foresters' reasons on re-defining the GIS-based site suitability classes. In addition, current land use status for each site is also provided to deem its land availability.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status			Remark / Justification
				Previous Forest Operations	Planted but need to be restored	Available	
1	Low	Low	BD-96			√	Agreed with the GIS result. Steep slope. Limited accessibility.
2	Low	Low	BD-61,69,70,71, 72		√		Overlapped with old unsuccessful plantation, established in 1989. Replanting is required. Limited accessibility.
3	Low	-	BD-91,92	√			Already planted.
4	Low	Unsuitable	BD-30,31,89			√	Core watershed (dam) zone.
5	Low	-	BD-98,107,108	√			Already planted.
6	Low	-	BD-107	√			Already planted.
7	Low	-	KY-4,5	√			Already Planted.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status			Remark / Justification
				Previous Forest Operations	Planted but need to be restored	Available	
			BD-106				
8	Low	Unsuitable	KY-37,39,40			√	Core watershed (dam) zone.
9	Low	Medium	SZa-15,17,18			√	No forest operation. Poor accessibility.
10	Low	Low	KY-34,37,38		√		Overlapped with old unsuccessful plantation, established during early 1980s. Replanting is required. Slope is steep especially in KY-38.
11	Low	-	KY-85,86	√			Already planted.
12	Low	Medium	SZa-53			√	No forest operation. Plantation labor can be obtained from nearby village but limited accessibility.
13	Low	Medium	SZa-11 SL-3			√	No forest operation. Plantation labor can be obtained but limited accessibility.
14	Low	-	KY-99,100,107	√			Already planted.
15	Low	Low	SL-3,7,8,9			√	Agreed with the GIS result.
16	Low	-	KY-99,107,110, 111	√			Already planted.
17	Low	Low	SL-14,16,17,18			√	Agreed with the GIS result.
18	Low	Low	SL-21,22			√	Agreed with the GIS result.
19	Low	Low	SZa-101, 103, 104, 109			√	Agreed with the GIS result.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status: Previous Forest Operations	Land Use Status: Planted but need to be restored	Land Use Status: Available	Remark / Justification
20	Low	-	KY-120,121,124	√			Already planted.
21	Low	Low	SL-26,27,29,30, 38,39			√	Agreed with the GIS result.
22	Low	Unsuitable	SZa-6,7			√	No forest operation but core watershed (dam) zone.
23	Low	Low	SZa-22,106			√	Agreed with the GIS result.
24	Low	Low	SL-35,36,37			√	Agreed with the GIS result.
25	Low	Unsuitable	SZa-5,6,7			√	No forest operation but core watershed (dam) zone.
26	Low	-	SZa-20,22,106	√			Already planted.
27	Low	Unsuitable	KY-120,121,124			√	No forest operation but core watershed (dam) zone.
28	Low	-	SZa-20,112	√			Already planted.
29	Low	-	SZa-20	√			Already planted.
30	Low	-	KY-140,142,145	√			Already planted.
31	Low	High	SZa-19		√		Overlapped with old unsuccessful plantation, established in 1990. Replanting is required.
32	Medium	Medium	BD-65	√		√	Agreed with the GIS result. Natural regeneration implemented in 2015.
33	Medium	Medium	BD-64,75			√	Agreed with the GIS result.
34	Medium	High	BD-65,66,67	√		√	Natural regeneration implemented in BD-65 and 66 in 2015. Very good accessibility.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status			Remark / Justification
				Previous Forest Operations	Planted but need to be restored	Available	
35	Medium	Medium	BD-63,64	√		√	Agreed with the GIS result. Natural regeneration implemented in BD-63 in 2015.
36	Medium	-	BD-83,84	√			Already planted.
37	Medium	-	BD-88,89	√			Already planted.
38	Medium	Low	BD-104,105			√	No forest operation. Close to dam.
39	Medium	Medium	BD-1,101,102, 103			√	Agreed with the GIS result.
40	Medium	Medium	BD-101,107			√	Agreed with the GIS result.
41	Medium	-	BD-108	√			Already planted.
42	Medium	-	BD-109	√			Already planted.
43	Medium	Medium	BD-110	√			Already planted.
44	Medium	Medium	BD-110,111	√			Already planted.
45	Medium	Low	SZa-55	√		√	Natural regeneration implemented in 2014.
46	Medium	Medium	SZa-15,17,18			√	Agreed with the GIS result.
47	Medium	Medium	SZa-44,55	√		√	Agreed with the GIS result. Natural regeneration implemented in SZa-55 in 2014.
48	Medium	Low	SZa-54,55	√		√	Natural regeneration implemented in SZa-54,55 in 2014. Limited accessibility.
49	Medium	Medium	KY-33,34,38,39		√		Agreed with the GIS result.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status			Remark / Justification
				Previous Forest Operations	Planted but need to be restored	Available	
							Overlapped with old unsuccessful plantation, established during early 1980s. Replanting is required.
50	Medium	Medium	SZa-13,14,15			√	Agreed with the GIS result.
51	Medium	Medium	SZa-41,55			√	Agreed with the GIS result.
52	Medium	Medium	SZa-13,15			√	Agreed with the GIS result.
53	Medium	Medium	KY-92,93		√		Overlapped with old unsuccessful plantation, established during early 1980s. Replanting is required.
54	Medium	Low	SZa-27,42	√		√	Natural regeneration implemented in SZa-27 in 2007 and in SZa-42 in 2010.
55	Medium	Low	SZa-26,27,42	√		√	Natural regeneration implemented in SZa-27 in 2007 and in SZa-42 in 2010.
56	Medium	Low	SZa-8,10,12	√		√	Natural regeneration implemented in SZa-8 and 10 in 2015. Also implemented in SZa-12 but it does not overlap.
57	Medium	Medium	SZa-10			√	No forest operation. Agreed with the GIS result.
58	Medium	Medium	SZa-26,27			√	Natural regeneration implemented in SZa-27 in 2007 but only small part. Agreed with the GIS result.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status			Remark / Justification
				Previous Forest Operations	Planted but need to be restored	Available	
59	Medium	Low	SZa-26,35,39,42	√		√	Natural regeneration implemented in SZa-26 in 2011.
60	Medium	Medium	SZa-26			√	Agreed with the GIS result. It does not overlap with implemented natural regeneration area.
61	Medium	Low	SZa-26	√		√	Natural regeneration implemented in 2011.
62	Medium	Low	SZa-7,12,24	√		√	Some parts overlapped with natural regeneration implemented in SZa-12 in 2015.
63	Medium	Low	SZa-34,35	√		√	Natural regeneration implemented in SZa-34 in 2007 and in SZa-35 in 2008.
64	Medium	-	KY-115,117	√			Already planted.
65	Medium	High	SZa-7,24			√	No forest operation. Close to settlements. Good accessibility. Available water supply for tree nursery.
66	Medium	Medium	SZa-104, 107			√	No forest operation. Agreed with the GIS result.
67	Medium	Medium	KY-119,120		√		Overlapped with old unsuccessful plantation. Replanting is required. Although site has good conditions, potential cattle disturbance exists. Thus, it was ranked as medium and agreed with the GIS result.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status			Remark / Justification
				Previous Forest Operations	Planted but need to be restored	Available	
68	Medium	Low	SL-30,31,38			√	No forest operation. Limited accessibility.
69	Medium	High	SZa-104,105, 106,107			√	No forest operation. Good accessibility. Available labor and water supply.
70	Medium	-	KY-119,120	√			Already planted.
71	Medium	Medium	SZa-104,107			√	No forest operation. Agreed with the GIS result.
72	Medium	Unsuitable	SZa-5,7			√	No forest operation but core watershed (dam) zone.
73	Medium	Low	SL-36,45,46,47, 48,49			√	No forest operation. Limited availability of sufficient labor. Potential water supply issues for tree nursery during summer.
74	Medium	Unsuitable	SL-53,58,85			√	No forest operation but core watershed (dam) zone.
75	Medium	Unsuitable	SZa-2,19,21			√	No forest operation but very close to pre-existing established plantations.
76	Medium	Unsuitable	SZa-2,19			√	No forest operation but very close to pre-existing established plantations.
77	Medium	-	KY-146,147, 148,149,150	√			Already planted.
78	Medium	-	SZa-1,2	√			Already planted.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status			Remark / Justification
				Previous Forest Operations	Planted but need to be restored	Available	
79	Medium	Medium	SL-90,93,95,96			√	Agreed with the GIS result.
80	Medium	Very High	SL-64,65,67 SZa-1,2		√		Already planted but only in small areas of SZa-1,2. Overlapped with old unsuccessful plantations, established during early 1980s. Replanting is required. Close to Bago river to fulfill water supply. Good accessibility.
81	Medium	-	SL-68 SZa-1	√			Already planted.
82	Medium	High	SZa-1 SL-65,66,67,68		√		Overlapped with old unsuccessful plantations, established during early 1980s. Replanting is required. Close to Bago river to fulfill water supply. Good accessibility.
83	Medium	Very High	SL-73,74,76			√	No forest operation. Close to settlements. Good accessibility.
84	Medium	-	SZa-1 SL-68,69	√			Already planted.
85	High	High	BD-68,81		√		Overlapped with old unsuccessful plantations, established in BD-68 in 1988 and in BD-81 in 1986.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status			Remark / Justification
				Previous Forest Operations	**Planted but need to be restored**	**Available**	
							Replanting is required. Good accessibility.
86	High	Low	SZa-55	√		√	Natural regeneration implemented in 2014. Limited accessibility.
87	High	High	KY-94,97		√		Overlapped with old unsuccessful plantations, established in 2000. Replanting is required.
88	High	Low	SZa-8,12			√	No forest operation but only very small part overlapped with pre-existing plantations in SZa-8. Thus, it was ranked as low.
89	High	-	SZa-106,107	√			Already planted.
90	High	-	KY-120,121	√			Already planted.
91	High	High	SZa-22			√	Agreed with the GIS result. Some parts overlapped with natural regeneration implemented in 2005. Good accessibility.
92	High	Very High	SZa-4 SL-55,56		√		Overlapped with old unsuccessful plantations, established in SL-55,56. Replanting is required. Close to well-grown teak seed production areas (SPA). Very good accessibility.
93	Very High	-	BD-80	√			Already planted.
94	Very High	Very High	BD-53,55,64,74			√	Agreed with the GIS result.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status			Remark / Justification
				Previous Forest Operations	Planted but need to be restored	Available	
							Bamboos dominate. Labor supply suffices.
95	Very High	Low	SZa-45,57	√		√	Overlapped with natural regeneration implemented in SZa-45 in 2015. Previous logged areas. Rather than plantation establishment, assisted natural regeneration was suggested.
96	Very High	-	KY-1,30 BD-111	√			Already planted.
97	Very High	High	KY-31,32,91,92	√			Already planted.
98	Very High	Medium	KY-94,95,96		√		Overlapped with old unsuccessful plantations, established during early 2000s. Vulnerable to cattle and fire hazard. Fire outbreaks customized the site into dry forests. Thus, fire protection measures are highly suggested. High illegal logging potential due to proximity to high way.
99	Very High	Very High	SZa-24,25			√	Agreed with the GIS result.
100	Very High	Very High	SZa-22,34,105			√	Agreed with the GIS result.
101	Very High	-	KY-119,120,121	√			Already planted.
102	Very High	Very High	SZa-3,4,5,7,29			√	Agreed with the GIS result.
103	Very High	-	SZa-3,23	√			Already planted.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status			Remark / Justification
				Previous Forest Operations	Planted but need to be restored	Available	
104	Very High	Very High	SL-50,51,92			√	Agreed with the GIS result.
105	Very High	-	KY-125,143, 145,146,147, 150,151	√			Already planted. The most successful teak plantation area.
106	Very High	Very High	SL-50,51,92			√	Agreed with the GIS result.
107	Very High	-	KY-150,151	√			Already planted.
108	Very High	Very High	SZa-1 SL-65, 67		√		Agreed with the GIS result. Overlapped with old unsuccessful plantations, established in1985. Replanting is required.
109	Very High	Very High	SL-79,81,82			√	Agreed with the GIS result.

Appendix B. Comparison of suitability classes for natural regeneration generated by GIS modeling versus defined by foresters

Table 30. Justifications of local foresters on modifying the GIS-based suitability classes for candidate assisted natural regeneration sites. Site IDs are linked with Figure 42 and Figure 43 which display the locations of each site. The GIS suitability classes and foresters' suitability classes are described in comparison. The reserved forest and compartment number of each site are also reported. BD means Baing Dar, KY means Kawliya, SL means Shwe Laung Ko Du Gwe and SZa means South Zamayi. The remark/ justification column provides the foresters' reasons on re-defining the GIS-based site suitability classes.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status		Remark / Justification
				Previous Forest Operations	Available	
1	Low	Low	BD-45,46,47,48		√	No forest operation. Limited accessibility.
2	Low	High	SZa-79		√	Site has good natural regeneration capacity.
3	Low	High	SZa-77,79		√	Site has good natural regeneration capacity.
4	Low	High	SZa-70,75,87		√	Site has good natural regeneration capacity. Overlapped with FD proposed site (SZa-70) to be naturally regenerated in 2024.
5	Low	Medium	SZa-93		√	Site has good natural regeneration capacity.
6	Low	Medium	SZa-94,97		√	Overlapped with FD proposed site (SZa-97) to be naturally regenerated in 2022.
7	Low	Medium	SZa-102		√	Overlapped with FD proposed site (SZa-102) to be naturally regenerated in 2022.
8	Low	High	SZa-93,94,95,97		√	Overlapped with FD proposed site (SZa-97) to be naturally regenerated in 2022.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status		Remark / Justification
				Previous Forest Operations	Available	
9	Low	High	SZa-103,110		√	Approximately 1.5 km away from FD proposed site (SZa-103) to be naturally regenerated in 2023.
10	Low	High	SZa-102,103,110		√	Very close (less than 0.5 km apart) to FD proposed sites: SZa-102 to be naturally regenerated in 2022; and SZa-103 in 2023.
11	Medium	Medium	BD-74		√	Agreed with the GIS result.
12	Medium	Medium	BD-48		√	Agreed with the GIS result.
13	Medium	Medium	BD-46,47		√	Agreed with the GIS result.
14	Medium	Medium	BD-45,47		√	Agreed with the GIS result.
15	Medium	Medium	BD-45,46		√	Agreed with the GIS result.
16	Medium	High	SZa-63		√	Site has good natural regeneration capacity. Repeated logging area and limited accessibility except old timber extraction paths. Situated next to FD proposed site to be naturally regenerated in 2026.
17	Medium	High	SZa-63		√	Situated next to FD proposed site to be naturally regenerated in 2026. Slope is steep in the area and thus, assisted natural regeneration is the only viable option.
18	Medium	High	SZa-63		√	Situated next to FD proposed site to be naturally regenerated in 2026. Slope is steep in the area and thus, assisted natural regeneration is the only viable option.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status		Remark / Justification
				Previous Forest Operations	Available	
19	Medium	High	SZa-79		√	Approximately 1 km away from FD proposed site to be naturally regenerated in 2026. Slope is steep in the area and thus, assisted natural regeneration is the only viable option.
20	Medium	High	SZa-77,79		√	Approximately 2 km away from FD proposed site to be naturally regenerated in 2026. Slope is steep in the area and thus, assisted natural regeneration is the only viable option.
21	Medium	High	SZa-77		√	Approximately 1.5 km away from FD proposed site to be naturally regenerated in 2026. Slope is steep in the area and thus, assisted natural regeneration is the only viable option.
22	Medium	Medium	SZa-70		√	Agreed with the GIS result.
23	Medium	Medium	SZa-70		√	Agreed with the GIS result.
24	Medium	Medium	SZa-70		√	Agreed with the GIS result.
25	Medium	Medium	SZa-93		√	Agreed with the GIS result.
26	Medium	Medium	SZa-93		√	Agreed with the GIS result.
27	Medium	-	SZa-54	√		Assisted natural regeneration implemented in 2014.
28	Medium	Medium	SZa-95		√	Agreed with the GIS result.
29	Medium	Medium	SZa-97,102		√	Agreed with the GIS result.
30	Medium	High	SZa-110		√	Site has good natural regeneration capacity. Approximately 2 km away from FD proposed site to be naturally regenerated in 2022.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status		Remark / Justification
				Previous Forest Operations	Available	
31	Medium	Medium	SZa-102		√	Agreed with the GIS result.
32	Medium	Medium	SZa-102,103		√	Agreed with the GIS result
33	Medium	Medium	SZa-102,103		√	Agreed with the GIS result.
34	Medium	Medium	SZa-97,101,102		√	Agreed with the GIS result.
35	Medium	Medium	SZa-101,103		√	Agreed with the GIS result.
36	Medium	High	SZa-102,103,110		√	Overlapped with FD proposed site (SZa-103) to be naturally regenerated in 2023.
37	Medium	High	SZa-110		√	Approximately 1 km away from FD proposed site to be naturally regenerated in 2023.
38	High	High	BD-55		√	Agreed with the GIS result.
39	High	High	SZa-63		√	Agreed with the GIS result.
40	High	High	SZa-77		√	Agreed with the GIS result.
41	High	Medium	SZa-102		√	Some parts overlapped with FD proposed site to be naturally regenerated in 2022. Accessibility is limited and falls within watershed zone. Thus, it was ranked as medium.

Appendix C. Comparison of suitability classes for community forestry generated by GIS modeling versus defined by foresters

Table 31. Justifications of local foresters on modifying the GIS-based suitability classes for candidate community forestry sites. Site IDs are linked with Figure 48. The reserved forest and compartment number of each site are also reported. BD means Baing Dar, KY means Kawliya, SL means Shwe Laung Ko Du Gwe and SZa means South Zamayi. The remark/ justification column provides the foresters' reasons on re-defining the GIS-based site suitability classes.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status		Remark / Justification
				Previous Forest Operations	Available	
1	Low	-	SZa-26,42	√		Natural regeneration implemented in 42. Limited accessibility.
2	Low	-	SZa-26,42	√		Natural regeneration implemented in 26.
3	Low	Low	SZa-26		√	Close to implemented natural regeneration area but not overlapped.
4	Low	-	SZa-26,35,39, 42	√		Natural regeneration implemented.
5	Low	-	SZa-26	√		Natural regeneration implemented.
6	Low	Medium	SZa-34,35,36		√	No forest operation. Good accessibility.
7	Low	-	SZa-6,7,8,12, 26, 27,42	√		Enrichment planting implemented in 12. Natural regeneration implemented in 12,27 and 47.
8	Low	Medium	SZa-25,26		√	Limited accessibility.
9	Low	High	SZa-7,24		√	No forest operation. Good accessibility. Close to settlements.
10	Low	Unsuitable	SZa-6,7		√	No forest operation but core watershed (dam) zone.
11	Low	Medium	SZa-104		√	No forest operation.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status		Remark / Justification
				Previous Forest Operations	Available	
						Good accessibility.
12	Low	Unsuitable	SZa-3,4,24		√	No forest operation but close to established plantations.
13	Low	-	SZa-22,105	√		Natural regeneration implemented.
14	Low	-	SZa-3,4	√		Already planted.
15	Low	Unsuitable	SZa-5		√	No forest operation but core watershed (dam) zone.
16	Low	Unsuitable	SZa-4		√	No forest operation but close to established plantations.
17	Low	-	SZa-104,105, 106, 107,108	√		Already planted.
18	Low	Unsuitable	SZa-20,22, 105,106		√	No forest operation but close to established plantations and implemented natural regeneration area.
19	Low	Unsuitable	SZa-23		√	No forest operation but close to established plantations.
20	Low	-	SZa-20,22	√		Already planted.
21	Low	Unsuitable	SZa-19,20,21		√	No forest operation but close to established plantations.
22	Low	-	SL-55	√		Unsuccessful plantation.
23	Low	-	SZa-20	√		Already planted.
24	Low	-	SZa-4 SL-55,56,60	√		Unsuccessful plantation.
25	Low	-	SZa-2,3,4 SL-60,61	√		Unsuccessful plantation.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status		Remark / Justification
				Previous Forest Operations	Available	
26	Low	-	SZa-2,19,21	√		Already planted.
27	Low	-	SL-19	√		Unsuccessful plantation.
28	Medium	-	SZa-12,27	√		Already planted (enrichment planting).
29	Medium	-	SZa-8,12	√		Natural regeneration implemented.
30	Medium	-	SZa-12,26	√		Already planted (enrichment planting)
31	Medium	-	SZa-12	√		Already planted (enrichment planting).
32	Medium	-	SZa-8	√		Natural regeneration implemented.
33	Medium	-	SZa-26,35	√		Natural regeneration implemented.
34	Medium	Medium	SZa-34		√	No forest operation.
35	Medium	Medium	SZa-7,12		√	No forest operation.
36	Medium	Unsuitable	SZa-7,24		√	No forest operation but core watershed (dam) zone.
37	Medium	Unsuitable	SZa-7		√	No forest operation but core watershed (dam) zone.
38	Medium	Medium	SZa-4,7,24		√	No forest operation.
39	Medium	-	SZa-3,23	√		Already planted.
40	Medium	Medium	SZa-22,23		√	No forest operation.
41	Medium	-	SZa-3,23	√		Already planted.
42	Medium	Medium	SZa-23		√	No forest operation.
43	Medium	-	SZa-4,5	√		Already planted.
44	Medium	Unsuitable	SZa-20,22		√	No forest operation but close to established plantations.
45	Medium	-	SZa-3,23	√		Already planted.
46	Medium	Unsuitable	SZa-21,23		√	No forest operation but close to established plantations.
47	Medium	-	SZa-4	√		Already planted.

Site ID	GIS Suitability Ranking	Foresters' Suitability Ranking	Reserved Forest/ Compartment No.	Land Use Status		Remark / Justification
				Previous Forest Operations	Available	
48	Medium	-	SZa-3,21,23	√		Already planted.
49	Medium	Unsuitable	SZa-19,20,21		√	No forest operation but close to established plantations.
50	Medium	-	SZa-4,5 SL-55,56	√		Unsuccessful plantation.
51	Medium	Unsuitable	SZa-2,21		√	No forest operation but close to established plantations.
52	Medium	-	SZa-1,2,19 SL-61	√		Already planted.
53	High	Medium	SZa-34		√	No forest operation. Close to settlements.
54	High	-	SZa-34,35	√		Natural regeneration implemented.
55	High	-	SZa-3,23	√		Already planted.
56	High	-	SZa-4,5	√		Already planted.
57	High	High	SZa-20,21,22,23		√	No forest operation. Good accessibility. Close to proposed community forestry village.
58	High	-	SZa-3,4,23	√		Already planted.
59	Very High	Very High	SZa-25,34		√	No forest operation. Good accessibility. Very close to proposed community forestry village. Possible agro-forestry. Lack of big trees.

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