博士論文

A research on developing optimal management plans with productivity and risk considerations for multi-species industrial tree plantations in the Philippines

(フィリピンにおける多樹種産業造林の生産性とリスクを考慮した最適計画の策定に関する研究)

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Executive Summary

In the Philippines, the significant loss of primary forest cover impelled industrial tree plantations to a major role in satisfying annual wood production requirements. Recently, wood production from plantations contributed more than 90% to the total annual log production of the country. However, the sustainability and stability of wood production from plantations are being jeopardized by the emergence of issues and limitations from the way they are developed and managed. In particular, management plans fail to implement proper species-site matching, lack provisions to include risk considerations, and fail to schedule timber harvests in an optimum manner. These limitations result from general problems such as lack of knowledge and limited availability of practical approaches for determining site productivity, risk assessment and harvest-schedule optimization. These issues and limitations are the motivations of this research study.

The study intended to seek approaches and solutions to the identified problems and consequently improve the current state of plantation development and management practices in the country. In order to do this, three sub-studies with interrelated objectives were conducted. The general objectives of this study are to, 1) determine site productivity for different target plantation species using the ecological characteristics of the site, 2) assess the site's probability of risk to wind damage brought by storms and typhoons, and 3) develop species-site assignment models that consider site productivity and risks and concurrently optimizes management objectives and timber harvest schedules.

The objectives of the study were applied on a case-study area in Caraga region, Mindanao, Philippines. The study site is a medium-scale industrial tree plantation area of softwood species located in a region where is there is a high prevalence of similar kind of plantations. In particular, the study focused on the 3,500-ha plantation area of the site in which four major plantation species are currently grown. These species are *Paraserianthes falcataria, Endospermum peltatum, Acacia mangium,* and *Gmelina arborea* which are grown to produce raw materials for the manufacture of veneer, pulpwood, matchwood and others. These particular species are also the target species

indicated in the study.

Plantation managers recognize the importance of proper species-site matching to achieve maximum growth of tree species. However, the lack of knowledge of the site's productivity impedes its implementation. In order to address this issue, the study sought the approach of determining site productivity from prevailing ecological characteristics. For each target species, the site productivity in terms of site index (SI) was estimated. Inventory data from various years and ecological factors mostly derived from digital elevation model (DEM) were used. Using multiple regression analysis, SI predictor models were developed and major ecological factors limiting site productivity for each species were identified. Results show that the accountability of best-fit SI predictor models ranges from 36% to 61%. Moreover, depending on the species, the predictor models included factors such as elevation, wetness index, exposure to direct solar radiation, length of sunlight duration and amount of annual rainfall. Common variable models using the elevation variable were also developed for all species to facilitate prioritization of multi-species over limited areas. The common variable models have lower accountabilities than best-fit models that range from 16% to 49%. Across target species, the best-fit models included different combinations of ecological variables confirming that site productivity is species-specific and is controlled not only by a single ecological factor, but by their combinations. Translating the results of SI models into maps showed the distribution of site index variation for each species across the study area. It also provided estimates of site productivity on areas inside the study site where the target species are not currently grown. These results demonstrated the feasibility of practical determination of site productivity from ecological factors. Further, this is an important information for plantation managers particularly those who manage multi-species plantations.

Risks to plantations come in many forms such as pest attacks and diseases, fire, wind damage and others. Considering these risks depending on their prevalence should be an important component of plantation management plans. The problem, however, is that risks that were not conceived before may have become relevant in the present. Such is the case of the study area where the unprecedented increase in the frequency of storms and typhoons is now causing serious wind damages to plantations. In this consideration, the site's probability of risk to wind damage was estimated empirically using logistic regression analysis. Specifically, the influence of stand-level attributes such as average stand height (ASH), elevation (Elev) and topographic exposure (TOPEX) on damage probability were assessed. For the analysis, post-storm inventory data from 2012 Typhoon Bopha in combination with previous stand inventory data were used. Logistic regression analysis yielded the best-fit model with the form,

$$P = \frac{\exp(-31.065 + 0.292ASH + 0.038Elev + 0.228TOPEX)}{[1 + \exp(-31.065 + 0.292ASH + 0.038Elev + 0.228TOPEX)]}$$

where, P is the probability of wind damage. Results showed that all three stand-level variables are influential and that damage probability has a direct relationship with the variables. By considering constant terrain conditions, the effect of average stand height was determined. Results indicated that there are critical average stand height levels which put each site at high risk of being damaged. Critical stand heights of 25 m, 20 m and 10-15 m were identified for low, medium and high-risk level sites. This information, when combined with site productivity, could be used as a basis for determining risk-sensitive rotation ages at which certain species can be grown while reducing wind damage to plantation. Moreover, variables used were derived from DEM thereby addressing the high-cost issue associated with developing damage probability models. Amidst the issue of climate change and the projected increase in weather disturbances, these results can improve management plans and make them relevant and responsive to changing times.

Finally, site productivity and risk considerations were integrated into an optimization model to develop species-site assignment models that maximize management objectives and ensure stability of future harvests. Results revealed feasible solutions to set management objectives using integer programming with binary variables. The study site was divided into management units called compartments and the optimum species assignment for each unit was identified using site productivity and risk-sensitive rotation ages. Results indicated that species-site assignment varies with different management objectives. Fast-growing and high-volume yielding species are prioritized in maximizing harvested volume objective. On the other hand, fast-growing and shorter rotation species are given more priority in the objective of maximizing net present value (NPV). In both objectives, *E. peltatum* was given the highest priority among target species. The risk-sensitive rotation ages used in optimal models revealed that in considering risks of wind damage, generally shorter rotation ages than usually practiced should be implemented. However, despite shorter rotation regimes, the optimal timber harvest schedules still yield high volumes of harvest and positive NPV for the 50-year planning period. Further, the resulting optimal models produced a harvest schedule with minimal fluctuations in harvested volume per working period, hence stable flow of income. Moreover, in pursuing both objectives, an adequate growing stock is ensured at the end of the planning period. Comparing optimal species-site assignment models and current species composition revealed that about 59% of the compartments are not planted with the recommended species. This indicates that the potential of the site in terms of timber volume production and NPV is not being maximized. These results demonstrated a scientific yet practical approach to solving plantation management problems related to site productivity, risks, species-site assignment and harvests. The integration of these results and approaches will improve plantation management and planning making them more flexible, scientifically-derived, relevant and responsive.

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***"I can do all things through Christ who gives me strength"*- Philippians 4:13**

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Chapter 1

Introduction

Background of the Study

In the global context, much emphasis is placed on the role of plantation forests for wood production. Although global total plantation area is a mere size compared to total forest cover, their importance is rapidly increasing as countries rely on them to sustainably meet increasing demand for wood pulp and energy (Sedjo, 1984; Yap, 2004; Carnus *et al.,* 2006; Bull *et al.,* 2006). Bull *et al.* (2006) related that the history of plantations particularly industrial forest plantations dates back to the 19^{th} century and significantly spread to tropical and subtropical countries in mid-20^{th} century. At the global level, the success of plantation development is driven by three major factors, 1) concern over stable wood supply and job creation, 2) industrial requirement for low-cost raw materials and, 3) attempt to decrease pressure on natural forests by shifting production to the other areas (Bull *et al.*, 2006).

In the Philippines, plantation forestry started as early as 1916 and boosted in late 1960s amidst the growing concern of the government about the declining forest resource (Niskanen and Saastamoinen, 1996; Paler *et al.*, 1998). By this time, the total forest cover of the country had significantly decreased to about 15.2 M ha from more than 20 M ha before the year 1920 and has continually declined to 6 M ha at present time (PCARRD, 2007; FAO, 2010). As a consequence, log production declined substantially with the loss of forest cover particularly that of primary forests (Figure 1.1). The drastic decline in forest cover set the Philippine government into motion by channeling funds for massive reforestation and development programs. In 1975, with the revision of the Forestry Code of the Philippines, much attention was given on establishing intensive industrial tree plantations (ITP) by enlisting the cooperation of private industries, individuals and other government agencies (Paler *et al*., 1998). Reforestation and plantation development were included as major components of tenurial instruments and socially-oriented programs such as; Community-Based Forest Management Agreement (CBFMA), Timber License Agreement (TLA), Integrated

Forest Management Agreement (IFMA), Tree Farm Lease Agreement (TFLA), Socialized Industrial Forest Management Agreement (SIFMA), Private Forest Development Agreement (PFDA), Forest Land Grazing Agreement (FLGMA) and Special and Land Use permits and agreements (SLUP).

However, the reforestation and plantation program from 1960s to late 1980s were beset with many problems and issues which rendered the efforts as total failure (DENR, 2003). The reforestation program was re-launched in 1986, but this time with more incentives to attract private investments (Paler *et al.*, 1998). These efforts led to an increase in investments in ITP and put industrial plantations in the forefront of wood production in the country. In 2012, statistics shows that total log production reached an amount of 862,429 m^3, in which 99.6% of the amount was produced from plantation forests (FMB, 2012).

The increasing importance of plantations in the Philippines is emphasized by its major role in satisfying demands for wood and wood-related products. Alongside with this role is the risk associated with it being a long-term investment involving huge capital expenditures and intermittent incomes. These two reasons strongly justify the need for plantation planning and management to be conducted in the most sustainable manner. The revised Master Plan for Forestry Development (MPFD) of the Philippines highly recognize the significance of forest plantations and identified the relevant issues that confront the successful and efficient implementation of forest plantation and development in the country (DENR, 2003). A lot of issues were identified, and they span across policies and legislation, technical and even research and development related problems. In terms of technical-related issues, the plan identified serious lapses in plantation development and management. These include poor species selection, disregard of species-site compatibility, plantation establishment and management, harvesting and absence of a scientific yet practical and systematic site classification system. These issues were also identified by authors Paler *et al.* (1998) and Harrison and Herbohn (2000) when they analyzed forest plantations of the country.

The issues mentioned above are often lacking or inadequately addressed in the development of management plans for industrial tree plantations. In addition to these problems, other limitations were observed in reviewing the management plans for industrial plantations. For most plantations, management is done in a systematic manner

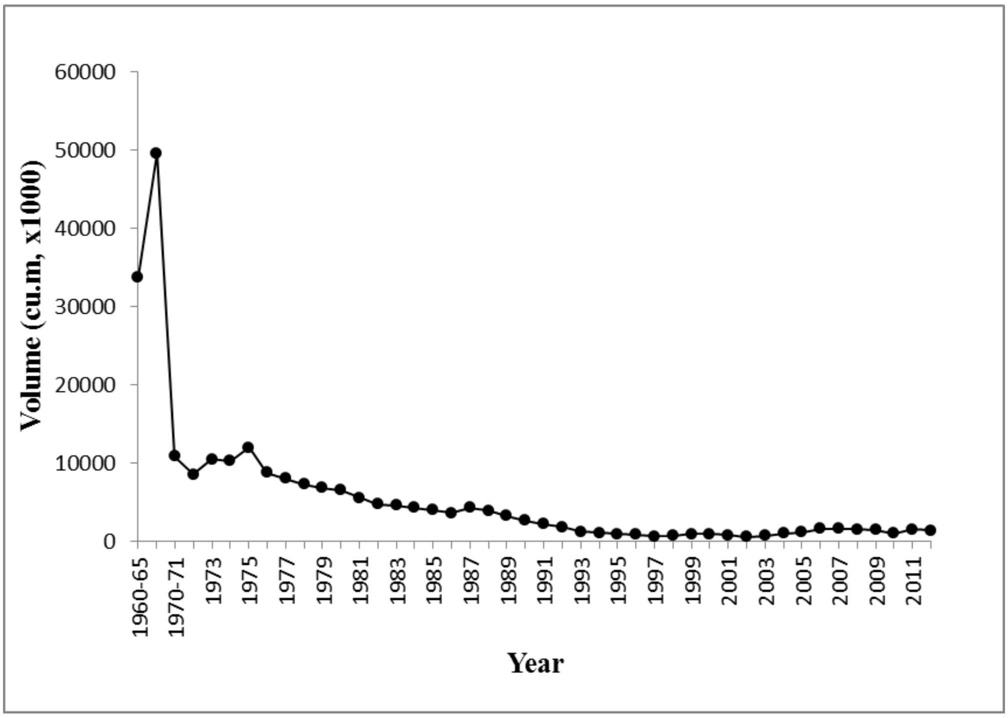

Figure 1.1 Log volume production (m^3) of the Philippines from 1960-2012 (FMB, 1992 and 2012)

and schedule of harvests follow the empirical approach of area control method. Issues arise however with the manner species are assigned to a site. It is evident that site assignment of species is not done scientifically but rather arbitrarily, which confirms the findings of the revised MPFD. In addition, risk management is found to be lacking in most management plans. Recent environmental changes like extreme weather events that may or may have caused damage to plantations are not accounted for in planning. These changes render the plan irrelevant and irresponsive when it fails to provide necessary actions when serious damages to plantation occur. Finally, harvest schedules do not indicate any level of optimization, and it is uncertain whether harvest volumes or profit are maximized and stabilized in the future years. The stable flow of harvests and income are prime considerations in a long-term investment like industrial plantations.

The limitations above highlight problems in some aspects of plantation development and management that ought to be addressed. Managers recognize the importance of considering site productivity to maximize growth and as a basis for site-species matching. However, it becomes a difficult task if the site productivity is unknown and methods of determination are not available for the forest manager.

Determining the productive potential of a relatively large area could be expensive and entail time-consuming site-species trials. The development of practical methods to estimate site productivity for multiple species is, therefore, necessary. In terms of risk management, it is important that the manager has knowledge of the site's level of risk to damaging factors. The development of probability risk models would help managers identify which sites are highly exposed to risk of damage. This information will also guide decisions related to species-site assignment and appropriate rotation regimes in the light of risk reduction objectives. Finally, the lack of optimization models that guide species-assignment decisions and harvest schedules should be addressed. These optimization models can serve as decision guides to ensure stability of future harvests and income.

The problems mentioned above confirm that problems related with plantation development and management continually evolve and change with time. It implies that management plans should be flexible and dynamic to be able to include these changes. This study focuses on resolving these problems and aims to contribute to the improvement of managing industrial plantations in the Philippines.

1.2 Objectives of the Study

The limitations and problems related to plantation development and management provide a potential avenue to improve the management of industrial tree plantations in the Philippines. Hence, this study was conducted. The general objectives of the study are to 1) determine site productivity for different target species using the ecological characteristics of the site; 2) assess the site's probability of risk to wind damage brought by storms and typhoons; and 3) develop species-site assignment models that consider site productivity and risks and concurrently optimizes management objectives and timber harvest schedules.

1.3 Structure of the Dissertation

This dissertation consists of six (6) chapters which integrate three (3) major studies that sought to address management issues associated with industrial tree plantations in the Philippines. Each study was designed to achieve different but interrelated objectives. An overview of the structure of this dissertation is given in Figure 1.2.

Chapter 1 introduces the importance of industrial plantations and plantation management in the Philippines. In addition, an explanation is given on the background information regarding the issues and challenges in plantation management that this study seeks to address. This chapter also presents the general objectives of the whole study as well as the description of the structure of this dissertation.

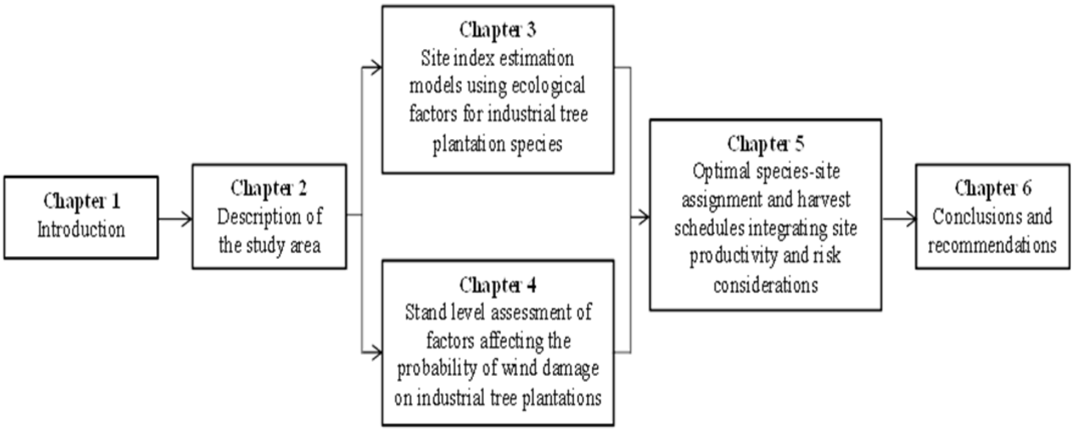

Figure 1.2 Structure of the dissertation

Chapter 2 provides a detailed description of the study area. It includes the prevailing biophysical characteristics, the silvicultural and current management practices being implemented in the site. It also describes the dominant plantation species which are also the target species in this study.

Chapter 3 introduces multiple regression models that predict species-specific site productivity for the four target species. This chapter identifies the main ecological site factors that determine site productivity for these species. The site index predictor models which are also linked to a spatially-referenced site index map will help forest managers determine site index variation and identify ground locations of sites best suited to each target species.

Chapter 4 discusses stand-level assessment of risks from wind damage resulting from destructive storms and typhoons. The study used site and stand characteristics to determine the probability of damage to the plantation after the occurrence of Typhoon Bopha in 2012. The models identified the site’s level of risk and critical stand height level at which it is highly susceptible to damage. This information could be translated to risk-sensitive rotation ages at which each site should be specifically managed in order to reduce the risk of wind damage.

Chapter 5 proposes optimal species-site assignment models that altogether maximize management objectives and provide harvest-schedules that satisfy stable harvest and income restrictions. These models maximize volume of harvest and net present value by taking into consideration site productivity and site risk level. This chapter integrates the findings of chapters 3 and 4 demonstrating the potential inclusion of site productivity considerations and risk management goals in determining optimal species-site assignment and timber harvest levels. Further, this chapter discusses the applicability of the proposed models for improving the existing harvesting schedule and consequently the management of industrial tree plantations in the Philippines.

Finally, Chapter 6 summarizes the results of three major studies mentioned above and enumerates the conclusions drawn from these studies. The important findings in the study are useful in improving the current management plan for industrial tree plantations. This chapter also provides recommendations and further research challenges that can help improve the findings of the study.

Chapter 2
Description of the study area

The study was conducted in an industrial tree plantation area in Agusan del Sur, Region 13 (Caraga), Mindanao Philippines. The plantation is being managed by the Casilayan Softwood Development Corporation (CSDC) under the Integrated Forest Management Agreement (IFMA). The study site was selected because it is located in the region where there is a predominance of industrial tree plantations and that at its scale it can well represent other plantations in the area. In addition, its approach to management planning showed the limitations and problems that this study sought to address. Lastly, inventory and other data to support this study are available for the site.

2.1 Location and background of study area

The study site is a 5,000-ha forest land in the province of Agusan del Sur, Region 13 in Mindanao, Philippines (Figure 2.1). It is located at 8^0 20' to 8^0 25' north latitude and $125^0$33' to $125^0$40' east longitude. The general terrain is gently sloping to moderately rolling with a mean elevation of 150 meters above sea level. The mean temperature is 26.6 ^{0}C, while mean annual rainfall is 2,900 mm. The area is divided into different land uses such as plantation forests, residual forest, grassland, wooded grassland, steep slope, fallow land, cultivated land and built-up area. The plantation forest, which is the focus of this study, covers about 70% (3,500 ha) of the total area, making it a major land use.

The study site is located in Caraga region (Region 13) dubbed as the timber corridor of the Philippines because of the presence of huge tracts of industrial tree plantations, mostly under the IFMA tenure scheme. This region because of its fertile lands and favorable weather is a major source of planted logs traded at local and international markets and marketed for various wood products. In 2012, the region produced a total of 584,257 m^3, which is more than 60% of the total log production of the country for that year (Figure 2.2), giving it a primary role in wood production in the country (FMB, 2012).

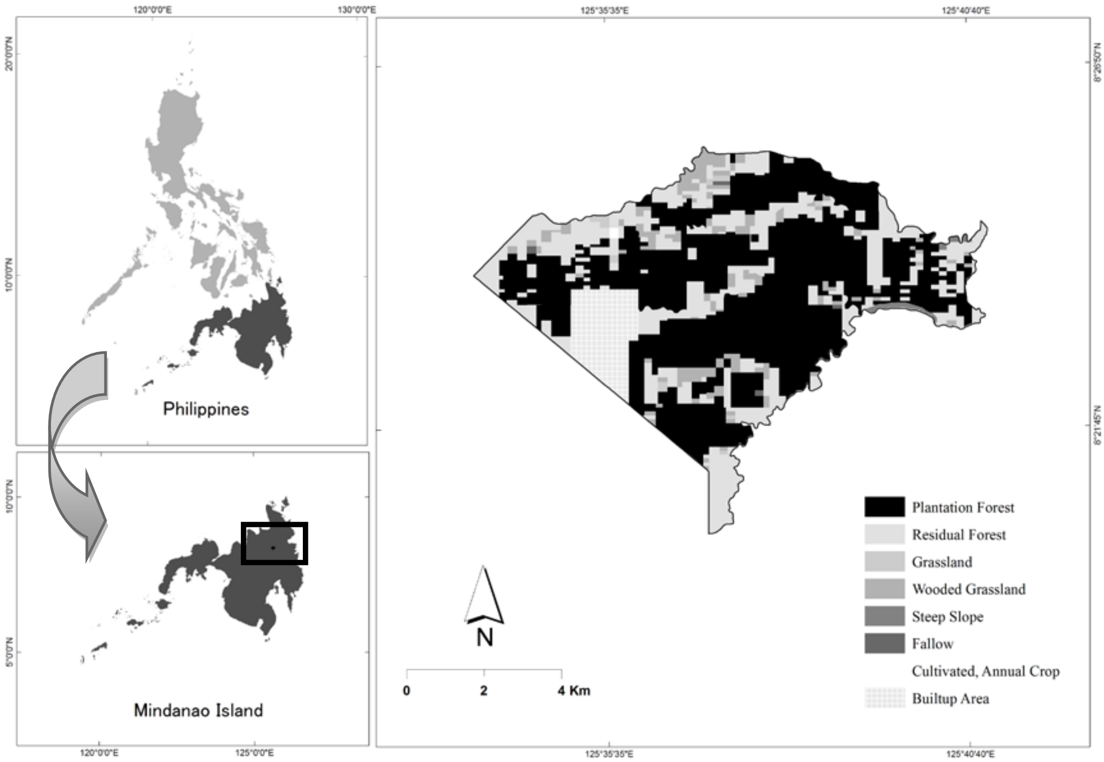

Figure 2.1 Location map of the study area

Back in 1976, the site was a logged-over area previously harvested for its dipterocarp forests under the timber license agreement. It was handed over to a new management in 1983 which leased the area under the industrial tree plantation license agreement (ITPLA) with the objective of converting the residual forest into a plantation of fast-growing softwood species. In 1992, the license was converted into an IFMA which is an agreement entered into by the Department of Environment and Natural Resources (DENR) and a qualified person or entity to occupy and possess in consideration of a specified rental, any forestland of the public domain in order to establish an industrial forest (FMB, 2012) . The objective of this IFMA is to develop and manage the 3,500 ha of industrial plantation forests of fast growing softwood species to supply the raw material requirement of wood processing plants.

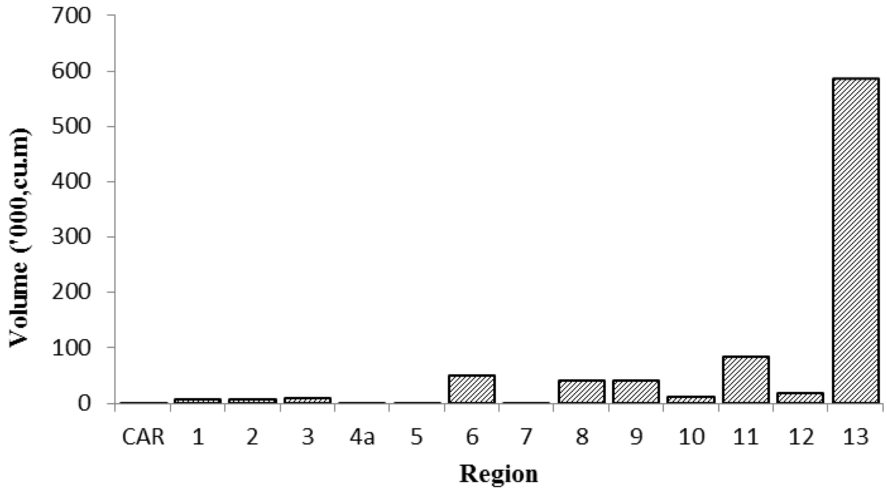

Figure 2.2 Log production (m^3) by region for the year 2012 (FMB, 2012)

2.2 Silvicultural system

The management applies the clearcutting system for its plantation area. Under this system, stands of *Endospermum peltatum* are grown and cut at a rotation age of 15-20 years while the three other plantation species; *Paraserianthes falcataria, Acacia mangium,* and *Gmelina arborea* are cut after 12 years. No thinning is applied throughout the rotation age, so the only the source of income is the final harvest. The silvicultural treatments applied on the plantation areas include pruning during the early stage of the plantation for trees ≤ 2 meters in height to minimize wood knots and application of fertilizers on young and seemingly poor performing plantations.

2.3 Forest resources of the study area

During the initial plantation establishment, the native species *E. peltatum* was planted as a major species because of its suitability as raw material for matchwood and other products. Other species were also planted as secondary species and for the purpose of breaking monoculture. As time goes by and with product diversification, *P. falcataria*, *A. mangium,* and *G. arborea* which are all fast-growing exotic species were also planted to provide raw material for veneer, pulp and paper, and matchstick production. These species which are also identified in the country's top 12 species grown for plantation purposes are the target species in this study (FMB, 2012).

Figure 2.3 shows the current age class structure of the growing stock where each age class represents two (2) years. Typical of a plantation, there is an abundance of young stands having an age of 6 years and below while relatively fewer areas in the more mature age classes. Because the stands are managed at a short-rotation, most stands are already harvested before they reach the 6th and 7th age classes resulting to an age structure that highlights the presence of more young stands than mature stands.

Figure 2.3 Current age class structure of growing stock in the study area

Past harvesting history on the plantation areas showed annual fluctuations in harvest volume from 1983 up until 2012 (Figure 2.4). There were some years (1986 and 1995) when there are no harvests from plantations resulting from government-imposed harvesting bans. Large fluctuations in years outside the logging ban indicate that with the current management plan, the stability of flow of harvests was not met and consequently the flow of income. This reflects the problems discussed in Chapter 1 and justifies the motivation of this study.

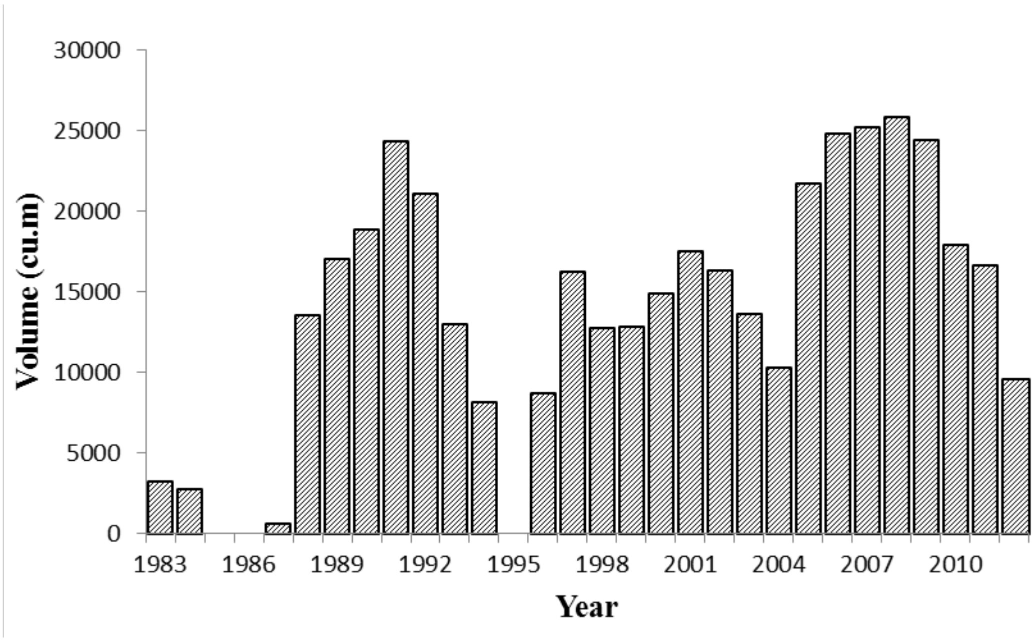

Figure 2.4 Volume harvested from plantation areas from years 1983 to 2012

Chapter 3

Site index estimation models using ecological factors for industrial tree plantation species

Forest plantations are mainly developed for wood production but may also be established to provide a wide array of services like wildlife habitat, biodiversity, aesthetics and other services (Packalen *et al*., 2011). The rapid increase in the world's population amidst the issue of increasing forest loss and degradation (Fox, 2000) amplifies the major role of forest plantations for timber production in meeting the world's increasing demand for wood. This issue and the increasing demand on forestlands for competing land uses serve as impetus for intensive management of plantation forests.

In intensive forest plantation management, higher growth rates could be achieved by concentrating timber production on best-adapted sites (Fox, 2000) or when species are properly matched with their site requirements (Harrison and Herbohn, 2000). In concept, the productivity of plants decrease when one of the environmental factors is out of the optimum growth range for the plant (Chen *et al*., 1998). This is usually accomplished through identification and evaluation of site quality specific to the target tree species. Site quality is defined as the innate productive capacity of the land area (Clutter *et al.,* 1983). Its evaluation characterizes the potential site productivity under a specified management regime and identifies associations between soil-site features and tree growth (Fox, 2000). The information derived from site quality evaluation aids forest managers in evaluating silvicultural implications (Louw and Scholes, 2002), assists in making cost-effective decisions about land-use and silvicultural investment levels (McKenney and Pedlar, 2003) and facilitates management decision-making and development of new technology (Fox, 2000).

Knowledge on site quality for forest management has been properly and thoroughly stressed in many studies in the past (Chen *et al*., 1998; Kayahara *et al*., 1998; Seynave *et al*., 2005; Mitsuda *et al*., 2007; Bosela *et al*., 2013). In terms of timber production, the widely used measure of site quality is site index, which is usually defined as the estimated height of the dominant trees at the site at a particular reference or base age (Carter and Klinka, 1990; Carmean, 1996; Iverson *et al*., 1997; Chen *et al*., 1998; Richardson *et al*., 1999; Davis *et al*., 2001; Hui-yan *et al*., 2001; Mitsuda *et al*., 2001; Nigh, 2002; McKenney and Pedlar, 2003; Seynave *et al*., 2005; Wang *et al*., 2005; Mathiasen *et al*., 2006; Mitsuda *et al*., 2007; Nunes *et al*., 2011; Packalen *et al*., 2011; Crechi *et al*., 2011; Bosela *et al*., 2013). The extensive use of site index in site quality evaluation is due to its close relation to volume growth and dominant height of most tree species in even-aged stands which is relatively unaffected by stand density and species mixture (Carter and Klinka, 1990; Carmean, 1996; Forss *et al*., 1996; Richardson *et al*., 1999).

There are two basic methods in evaluating site quality in terms of site index: direct (phytocentric) and indirect (geocentric) (Clutter *et al.*, 1983;Socha, 2008;Bosela *et al*., 2013). The former involves direct measurement of the average height of dominant trees at a certain base age while the latter associates site index with ecological factors. The direct approach provides a simple and efficient tool for estimating site index with the use of height growth models for mature stands or growth intercept models for young stands with free-growing trees (Chen *et al*., 1998). However, it has some drawbacks. Direct measurement of site index cannot be done in tree-less areas or in sites where the concerned species is not present (Chen *et al*., 1998; Corona *et al*., 1998; McKenney and Pedlar, 2003; Wang *et al*., 2005; Bosela *et al*., 2013). It also imposes strict stand characteristic restrictions (age and stocking) before it can be successfully applied to predict site quality in other areas. In cases like these, the indirect site index measurement seems to be more favorable.

The indirect method assumes that site productivity is determined by factors directly affecting plant growth which are solar radiation, temperature, water, nutrients, soil aeration, and biotic interactions (Chen *et al*., 1998). There are two main approaches in implementing indirect site index measurement: synoptic and analytic. In the synoptic approach, site index is correlated with site or soil classes, whereas the analytic approach involves modelling site index as a function of various ecological, topographical, and soil variables (Seynave *et al*., 2005; Socha, 2008; Bosela *et al*., 2013).

A wealth of studies had been published on evaluating site index using the analytic approach, particularly for temperate tree species. These studies used various kinds and different categories of ecological variables to predict site index variability.

Most of these studies employed multiple regression analysis that used a number of topographic, soil physical, and soil chemical properties as independent variables to predict site indices (Richardson *et al*., 1999; Mitsuda *et al*., 2001; Bosela *et al*., 2013). One of the early works on this subject was that of Hagglund and Lundmark (1977), which expressed in mathematical functions the dependence of site index of Scots pine and Norway spruce in Sweden with factors such as geographical location, ground vegetation and soil properties.

The commonly investigated ecological variables are topography, climate and soil (Chen *et al*., 1998). Examples of these variables are latitudinal and longitudinal gradients, elevation, slope, aspect, rainfall, temperature, soil moisture, soil nutrients, soil depth, physical and chemical soil properties. Succeeding studies investigated site correlations with topographical exposure (Corona *et al*., 1998; Curt *et al*., 2001), growing season water deficit (Carter and Klinka, 1990), soil aeration regimes (Wang and Klinka, 1996), forest floor characteristics and foliar nutrients (Chen *et al*., 1998), biogeoclimatic zones (Chen *et al*., 2002), understorey vegetation (Seynave *et al*., 2005), solar radiation index (Mitsuda *et al*., 2007), soil parent rock (Socha, 2008), and length of growing season (Bosela *et al*., 2013).

In the advent of technological advances, tools like geographic information systems (GIS) and remote sensing (RS) made estimation of ecological characteristics on large areas more convenient limiting the need for extensive field surveys. These technological advances made possible the calculation of ecological variables from remotely-sensed data and digital elevation models (DEM). As a result, more ecological factors were being added to model site index variability. Iverson *et al*. (1997) used GIS to develop an integrated moisture index (IMI) from DEM of different resolutions, which was then used to predict oak (*Quercus* spp.) site index and species composition for forests in Ohio. In this study, several landscape features such as slope-aspect shading index, cumulative flow of water downslope, curvature of the landscape, and soil water-holding capacity were considered in creating the IMI. The statistical relationships obtained were then imported GIS to come up with maps of site index and composition. In 2006, Mingdong *et al*. correlated spruce site index with remotely-sensed data such as normalized difference vegetation index (NDVI) and soil adjust vegetation index (SAVI). In Japan, site index models for Sugi (*Cryptomeria japonica*) (Mitsuda *et al*., 2007) and

Japanese larch (Mitsuda *et al*., 2001) were constructed from DEM-based environmental factors.

In the Philippines, the rapid decline of forest cover due to illegal and commercial exploitations impelled the massive reforestation programs for timber production and environmental purposes (Harrison and Herbohn, 2000). Several introduced species such as *Gmelina arborea*, *Paraserianthes falcataria*, *Tectona grandis*, *Swietenia macrophylla* and *Acacia mangium* and native species *Eucalyptus deglupta*, *Melia dubia* and *Endospermum peltophorum* were used in the reforestation and plantation development programs. However, poor growth and vigor frustrate these efforts. One reason is improper site-species matching (Harrison and Herbohn, 2000) which could be attributed to lack of knowledge on site productivity of reforestation areas. Most, if not all, efforts to measure species-specific site index in the Philippines used the direct approach. Unfortunately, there is a dearth of studies investigating the relationship between site index and site factors of major plantation species, thus the lack of information on site productivity of candidate sites for reforestation and plantation development. This study aims to fill that knowledge gap and provide managers a practical way of determining site productivity that could then be used for site-species matching and other related decisions.

The objectives of the study are (1) to identify the main ecological factors affecting site index variability of four major industrial tree plantation species in Mindanao region, Philippines – *P. falcataria, E. peltatum, A. mangium* and *G. arborea*; (2) to develop best fit site index predictor model for each species; and (3) to develop a common variable site index model for the plantation areas.

2.2 Methodology

2.1.1 Data Collection

Data from inventory activities conducted in 2007, 2011 and 2013 were used in the study. In the inventory, 0.1-0.2 ha sample plots were laid out throughout the study area, tree diameter at breast height (DBH) and total height (TH) for all standing trees were measured. Plot locations were recorded on maps, and plot ages were verified from plantation maps and planting records. Inventory plots located inside the plantation areas containing the target species were selected as sample plots for the study. The inventory plots which contain an overlap of target species were segregated and the characteristics were determined according to the specific target species. The sample plots were then randomly split into two sets, one for model development and the other set for model validation. The tallest trees of each species from each sample plot were chosen as site trees, and their mean height was determined to obtain an estimate of the dominant height. Summary statistics of the sample plots used and the corresponding site factors are shown in Table 3.1.

The sample plots are well-distributed over the study area to cover a wide range of variation in each ecological factor. However, there are still some cases where only a small portion of the site factor variability was considered. But in general, the study considered a sufficient proportion of the possible values of ecological factors throughout the study area. Further, the samples were located in plantation areas where productivity related planning and evaluation were focused.

2.1.2 Ecological factors

Raster maps of ecological factors were derived and processed from an ASTER-DEM with 30 m resolution and processed in ArcGIS 10.2. The following ecological factors were used in this study: elevation (E), slope (S), topographic position index (TPI), curvature (C), shading (SH), wetness index (WI), sunlight duration (SD), direct solar radiation (SR), topographic exposure (TPX), and annual rainfall (RAIN). These factors were chosen based on the results of previous studies on their potential effect on site index. In addition, most of them can be derived easily from DEM data. The factors were categorized into topography, soil moisture, solar and wind and climate variables.

Topographical variables include elevation (E), slope (S) and topographic position index (TPI). E was obtained from the DEM while S was calculated as the maximum change in elevation over the distance between the cell and its neighbors in a 3-by-3 cell environment. A lower slope value indicates a flatter terrain while a higher value represents steep slopes. On the other hand, TPI was computed as the difference between a cell elevation value and the average elevation of the neighborhood around that cell (Majka *et al.*, 2007). A 5-cell circular neighborhood was used in the study. Positive TPI values mean the cell is higher than its surroundings while negative values mean it is lower than the neighboring cells. TPI values near 0 mean that the elevation is close to the mean elevation of the neighbor cells, which usually happens in flat or mid-slope areas. TPI was calculated using the Land facet corridor extension toolset created by Majka *et al*. (2007).

In the absence of data on soil characteristics, DEM-derived ecological variables related to soil moisture such as curvature (C), shading (SH) and wetness index (WI) were used. C is defined as the inclination of the slope, which describes a landform (Iverson *et al.,* 1997, Mitsuda *et al.*, 2001). C values used in this study were derived from the profile curvature output raster of the curvature tool. Positive curvature values indicate that the surface is upwardly concave while a negative curvature indicates that the surface is upwardly convex. Meanwhile, a value of 0 means that the surface is flat. Curvature is used to model exposed and sheltered sites, as well as flow acceleration. SH was created using the shaded topography, where SH was calculated as the brightness of the surface considering local illumination angle. In this case, shadowed or brightly lit areas are determined from the northwesterly direction (azimuth angle is 315^0, and solar elevation angle is 45^0). Increasing SH values indicate increasing brightness or surface illumination. On the other hand, Wetness Index (WI) is calculated using the formula, $WI= \ln (A_s/\tan ß)$, where A_s is the catchment area and ß represents the slope gradient. This equation assumes steady state conditions and uniform soil properties. It is used to predict zones of saturation along drainage paths and in zones of water concentration in landscapes (Wilson and Gallant, 2000). Wetness index was calculated from a filled DEM by filling in sinks using Hydrology toolset while the final wetness index map was computed from flow-path lengths and upslope contributing areas. Increasing WI values are observed from the ridge to valley bottoms and riverbeds.

The probable solar and wind related effects were investigated using sunlight duration (SD), direct solar radiation (SR) and topographic exposure (TPX) variables. SD and SR were derived using the solar radiation toolset, where SR was calculated as the incoming direct solar radiation from a raster surface considering latitudinal area

Table 3.1 Summary statistics of sample plots used for site index model development

Variables	*P. falcataria* n_m= 286 n_v = 52		*E. peltatum* n_m= 238 n_v = 51		*A. mangium* n_m= 53 n_v = 18		*G. arborea* n_m= 75 n_v = 25	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Tree Density (tree/ha)	321	40-515	187	40-700	44	30-110	236	30-813
Average DBH (cm)	26	17-32	24	16-34	22	17-30	24	17-29
Average TH (m)	15	9-18	14	9-20	13	8-18	13	11-15
Basal Area per ha (m^2/ha)	17	1-33	8	1-42	2	1-4	10	1-40
Total Volume per ha (m^3/ha)	170	8-364	75	6-389	16	8-40	78	5-331
Age (years)	8	3-9	5	2-14	9	4-13	8	3-13
Dominant DBH (cm)	39	17-55	30	17-46	25	20-40	27	17-42
Dominant TH (m)	19	11-25	17	11-22	15	11-22	16	12-20
Site Index (m)	21	16-27	33	16-47	15	8-26	19	14-26
Elevation (m)	109	62-181	119	66-183	114	67-172	130	57-198
Slope (^{0})	7	2-25	10	2-26	8	2-19	12	2-33
Topographic Position Index (m)	1	-15-27	1	-20-32	1	-7-15	2	-15-15
Curvature	-0.03	-1.8-0.9	-0.05	-1.8-1.4	0.01	-0.4-0.5	-0.02	-0.9-0.9
Shading	178	103-226	180	109-232	173	120-208	173	109-244
Wetness Index	7	4-11	7	5-11	7	5-9	6	5-10
Sunlight Duration (hours/year)	4191	3759-4337	4099	3375-4333	4162	3875-4300	4094	3535-4329
Direct Solar Radiation (kcal/cm^2)	119	110-122	118	101-122	119	114-122	117	99-122
Topographic Exposure	215	198-217	213	196-217	215	206-217	211	184-217
Annual Rainfall (mm)	2913	2837-3013	2881	2787-2982	2874	2786-3002	2843	2786-3013

n_m = number of sample plots used for model development, n_v = number of validation plots

location, slope, and aspect data. SR was estimated for the whole year. Increasing SD and SR values mean longer and higher exposure to solar radiation, respectively. Meanwhile, TPX describes the protection or exposure of a given site by the surrounding topography. This factor gives an idea of the degree of openness of a given site, which relate to wind and water dynamics. TPX in this study was modeled using the shade topography averaged from 16 maps of the cardinal and ordinal directions (N, NE, E, SE, S, SW, W, NW) using 45^0 and 90^0 elevation angle for each azimuth direction. Increasing TPX values indicate increasing levels of exposure.

The climatic ecological variable represented by the amount of annual rainfall (RAIN) was used to determine the effect of climate variability on site index. The availability of climate data in the Philippines is generally limited and for this study the data of mean annual rainfall from three weather stations (Butuan City, Malaybalay City and Hinatuan City) with the shortest proximity to the study area were used. Rainfall data from 2002-2012 from these weather stations were collected from the database of Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAG-ASA) and values were averaged to determine the 10-year mean values. The values were then interpolated using inverse distance weighted (IDW) function to estimate the local climatic conditions in the study area.

2.1.3 Data Analysis

In this study, site index was related to ecological variables by first determining the measured site index value of each sample plot for the respective target species using published site index equations at a certain base age (Table 3.2). Then, a correlation analysis was conducted to investigate the degree of linear relationship between and among the variables. The following linear relationship between SI and ecological factors was assumed,

$$SI = \alpha + \beta X_1 + \beta X_2 + \beta X_2 + \ldots. + \varepsilon$$

where, site index (SI) is a multiple linear function of ecological factors (X_i), their coefficients (β_i) and error (ε) (Corona *et al*., 1998; Fontes *et al*., 2003; Ercanli *et al*., 2008).

Table 3.2 Published site index equations used to determine measured site index for each target species

Species	Equation	Base Age	Author
P. falcataria	Log SI = 0.41834 + Log H – 0.41834 Log A	10	(Revilla 1974)
E. peltatum	Log SI = 0.69879 – 0.59416 Log A + Log H	15	(Ramos 1977)
A. mangium	Log SI = Log H + 0.8955 (Log BA – LogA)	8	(Palma et al. 2006)
G. arborea	Log SI = -0.06139 + Log H +0.92094/A	15	(Lingan 1979)

Base Age in years, SI = site index (m), H = dominant height (m) and A = age in years

Since the form of the model is unknown, several procedures were employed to select the variables that will be considered in the best model selection. The variable selection procedures included an exhaustive search for the best variable subsets using an efficient branch-and-bound algorithm with Bayesian Information Criterion (BIC) results and backward stepwise regression using Akaike Information Criterion (AIC). The ecological variables most frequently selected from the two procedures were tested using multiple linear regression analysis where the best predictor model was dictated by the regression statistics.

Multicollinearity among variables was minimized by dropping models whose beta-coefficients have conflicting signs and with very high variance inflation factor (VIF). A VIF value of more than 10 indicates the existence of serious multicollinearity problem and masks the true relationship between the predictor and response variables; so this should be carefully examined.

Regression analyses were performed for each set of grouped variables and their combinations to test the effect of different ecological variables on site index. The best fit model is then selected from all significant models based on the adjusted coefficient of determination (adjusted R^2) and standard error of estimate (SEE). Individual regression statistics such as standard regression coefficients (SRC) and partial coefficient of determination (PCD) for the best models were also estimated. The independent variables tested were measured in different units, so SRC is estimated to see the actual effect of each independent variable using the same unit. On the other hand, PCD reflects the actual prediction power of each independent variable with regards to the dependent variable by withholding the impact of other independent variables in the model.

In addition, models using a common set of variables for all species were developed. The common variable models are comprised of a single or a group of variables which are significant and common for all species. The reason for this is in order to facilitate identification and prioritization of species for a specific area in a mixed or multi-species plantation set-up. A common variable model will aid in simplifying comparisons and in combination with other information can guide in species-area assignment over productivity optimization objectives.

All statistical analyses were done using R (R Core Team, 2013) in RStudio (RStudio, 2012).

2.2 Results

2.2.1 Correlation Analysis

The relationships between site index and ecological factors for each species are given in Tables 3.3-3.6.

Table 3.3 Pearson's correlation coefficient between site index of *P. falcataria* and ecological factors

	SI	E	S	TPI	C	SH	WI	SD	SR	TPX	RAIN
SI	1.00										
E	-0.41**	1.00									
S	-0.13*	0.29**	1.00								
TPI	-0.13*	0.15**	0.18**	1.00							
C	0.11	-0.17**	-0.16**	-0.66**	1.00						
SH	0.12*	-0.13*	-0.27**	-0.04	-0.01	1.00					
WI	0.27**	-0.20**	-0.53**	-0.56**	0.38**	0.11	1.00				
SD	0.10	-0.11	-0.56**	0.46**	-0.37**	0.13*	0.00	1.00			
SR	-0.18*	0.05	-0.62**	-0.09	0.11	-0.31**	0.30**	0.33**	1.00		
TPX	0.08	-0.30**	-0.95**	-0.17**	0.18**	0.33**	0.44**	0.51**	0.59**	1.00	
RAIN	0.71**	-0.79**	-0.32**	-0.05	0.13*	0.08	0.20**	0.26**	0.01	0.29**	1.00

** significant at α= 0.01, *significant at α= 0.05

The site index of *P. falcataria* is positively correlated with SH, WI and RAIN and is negatively correlated with E, S, TPI, and SR. It decreases with an increase in elevation (r=-0.41), slope (r=-0.13 and topographic position (r=-0.13). Similarly, site index decreases with an increase in exposure to direct solar radiation (r=-0.18). On the other hand, it increases with an increase in shade value (r=0.12) and wetness index (r=0.27). Site index is also expected to increase with an increase in the amount of rainfall (r=0.71).

Table 3.4 Pearson's correlation coefficient between site index of *E. peltatum* and ecological factors

	SI	E	S	TPI	C	SH	WI	SD	SR	TPX	RAIN
SI	1.00										
E	-0.70**	1.00									
S	-0.08	0.08	1.00								
TPI	-0.28**	0.32**	0.11	1.00							
C	0.16*	-0.19**	-0.09	-0.70**	1.00						
SH	0.24**	-0.26**	-0.02	-0.13*	0.02	1.00					
WI	0.37**	-0.43**	-0.36**	-0.60**	0.32**	0.16*	1.00				
SD	-0.13*	0.07	-0.45**	0.58**	-0.38**	-0.12	-0.22**	1.00			
SR	-0.22**	0.24**	-0.72**	0.13*	-0.06	-0.49**	0.07	0.51**	1.00		
TPX	0.04	-0.01	-0.96	-0.09	0.10	0.01	0.29	0.43**	0.74**	1.00	
RAIN	0.60**	-0.44**	-0.28**	-0.17**	0.13*	0.05	0.20**	-0.05	0.04	0.21**	1.00

** significant at α= 0.01, *significant at α= 0.05

For *E. peltatum*, site index is found to be positively correlated with C, SH, WI, and RAIN. On the other hand, it is negatively correlated with E, TPI, SD and SR. In terms of topography, site index decreases with both an increase in elevation and topographic position (E:r=-0.70; TPI:r=-0.28). In the same manner, site index is observed to be lower in areas with longer and higher exposure to sunlight (SD:r=-0.13; SR:r=-0.22). But site index is higher in concave areas (r =0.16) with minimal shading (r=0.24), located near valley bottoms and rivers (r=0.37) and which receives ample amount of rainfall (r=0.60).

Table 3.5 Pearson's correlation coefficient between site index of *A. mangium* and ecological factors

	SI	E	S	TPI	C	SH	WI	SD	SR	TPX	RAIN
SI	1.00										
E	-0.54**	1.00									
S	-0.04	0.38**	1.00								
TPI	-0.13	0.31*	0.06	1.00							
C	-0.02	-0.07	-0.34**	-0.51**	1.00						
SH	0.16	-0.30*	-0.46**	-0.09	0.10	1.00					
WI	0.13	-0.36**	-0.50**	-0.55**	0.40**	0.21	1.00				
SD	-0.09	-0.14	-0.66**	0.40**	-0.04	0.24	0.12	1.00			
SR	-0.40**	0.23	-0.46**	-0.13	0.27*	-0.26	0.26	0.30*	1.00		
TPX	0.02	-0.32**	-0.96**	-0.08	0.37**	0.53**	0.48**	0.60**	0.42**	1.00	
RAIN	0.43**	-0.80**	-0.49**	0.01	-0.06	0.23	0.25	0.38**	-0.07	0.40**	1.00

** significant at α= 0.01, *significant at α= 0.05

The site index of *A. mangium* showed significant positive correlation with RAIN variable and negative correlation with E and SR. It decreases with an increase in altitude (r=-0.54) and direct solar radiation (r=0.40). On the other hand, site index for this species is observed to increase with an increase in rainfall amount (r=0.43).

Table 3.6 Pearson's correlation coefficient between site index of *G. arborea* and ecological factors

	SI	E	S	TPI	C	SH	WI	SD	SR	TPX	RAIN
SI	1.00										
E	-0.49**	1.00									
S	-0.12	0.13	1.00								
TPI	-0.36**	0.50**	0.07	1.00							
C	0.22	-0.24*	0.00	-0.59**	1.00						
SH	0.34**	-0.20	-0.07	-0.18	0.10	1.00					
WI	0.43**	-0.46**	-0.56**	-0.61**	0.32**	0.18	1.00				
SD	-0.28*	0.16	-0.66**	0.49**	-0.42**	-0.20	0.07	1.00			
SR	-0.16	-0.04	-0.75**	0.02	-0.11	-0.48**	0.33**	0.70**	1.00		
TPX	0.00	-0.05	-0.96**	-0.06	-0.01	-0.03	0.47**	0.65**	0.80**	1.00	
RAIN	0.65**	-0.45**	-0.35**	-0.18	0.15	0.15	0.41**	0.02	0.11	0.23*	1.00

** significant at α= 0.01, *significant at α= 0.05

Lastly, for *G. arborea* the variables SH, WI and RAIN displayed a significant positive relationship with site index whereas a negative relationship was observed with E, TPI, and SD. Site index decreases significantly with positive changes in elevation (r=-0.49) and topographic position index (r=-0.36). It is also observed to decrease in areas having longer exposure to sunlight (r=-0.28). On the contrary, it increases with increasing shade and wetness index value (SH:r=0.34; WI:r=0.43) and at the same time with increasing rainfall amount (r=0.65).

2.2.2 Multiple Linear Regression Analysis

Site index variability for the target species was modeled using regression analysis per variable group, combination of ecological variables and common variable models. All accepted models are significant ($p<0.000$) and all variables of these models are significant at $\alpha=0.05$.

Table 3.7 Regression statistics of site index model groups

Model group	No	Variable	*P. falcataria*			*E.peltatum*			*A. mangium*			*G. arborea*		
			Adj. R^2	SEE	p-value	Adj. R^2	SEE	p-value	Adj. R^2	SEE	p-value	Adj. R^2	SEE	p-value
Topography	1	E	0.161	1.776	0.000	0.490	4.196	0.000	0.287	3.813	0.000	0.220	2.514	0.000
	2	E,S	-	-	-	-	-	-	0.319	3.727	0.000	-	-	-
Soil	3	C,SH	-	-	-	0.078	5.643	0.000	-	-	-	-	-	-
	4	SH, WI	-	-	-	0.162	5.382	0.000	-	-	-	0.221	2.512	0.000
Wind	5	SD, SR	0.055	1.875	0.000	-	-	-	-	-	-	-	-	-
	6	SR,TPX	0.079	1.851	0.000	0.134	5.470	0.000	-	-	-	0.060	2.765	0.046
	7	SD, TPX	-	-	-	-	-	-	-	-	-	0.117	2.675	0.004
Climate	8	RAIN	0.504	1.358	0.000	0.358	4.709	0.000	0.168	4.122	0.001	0.437	2.136	0.000

Table 3.7 shows the list of all accepted models per variable group. In terms of topography, the single variable model using E (Model 1) is the only model that turned out to be significant for all species. Site index model combining E and S (Model 2) were significant for *A. mangium* only. Regressions of site index and soil moisture variables (C, SH and WI) were significant for species *E. peltatum* and *G. arborea*. Soil moisture model using SH and WI (Model 4) was significant for both *E. peltatum* and *G.*

arborea while the model combining C and SH (Model 3) was only significant for the former. On the other hand, regressions between site index and solar and wind related variables (SD, SR and TPX) appeared significant for *P. falcataria* (Model 5 and 6), *E. peltatum* (Model 6) and *G. arborea* (Model 6 and 7) species only. The climatic model using RAIN variable (Model 8) is significant for all species.

For *P. falcataria* and *G. arborea*, the best performing model group is the climate model followed by the topography model. Model 8 can predict as much as 50% and 44% of the site index variability in *P. falcataria* and *G. arborea,* respectively while the prediction power of model 1 is only about 16-22%. The opposite is true for *E. peltatum* and *A. mangium* where topography models performed better than climate models. For *E.* peltatum, the adjusted R^2 value of model 1(0.490) is higher than that of model 8 (R_a^2 = 0.358). Similarly for *A. mangium*, models 1 and 2 outperformed model 8 with R_a^2 = 0.287 ; 0.319 and SEE=3.813; 3.727, respectively. For all species, models related to soil moisture and solar and wind performed poorly, with predictive power of less than 22%.

Table 3.8 Form of the best-fit integrated models for each target species

Model No.	Species	Equation	Adj. R^2	SEE	p-value
9	a	SI = -35.616 + 0.314 (WI) – 0.225 (SR) + 0.028 (RAIN)	0.576	1.256	0.000
10	b	SI = -95.604 – 0.128 (E) + 0.405 (WI) – 0.222 (SR) + 0.058 (RAIN)	0.609	3.677	0.000
11	c	SI = 108.821 – 0.118 (E) – 0.678 (SR)	0.360	3.615	0.000
12	d	SI = -58.237 – 0.019 (E) – 0.004 (SD) + 0.034 (RAIN)	0.522	1.969	0.000

Species letters a,b,c,d correspond to the following: a = P. falcataria, b = E. peltatum, c = A. mangium, d= G. arborea

The results of the regression between site index and the combination of ecological variables (Table 3.8) yield higher accountabilities than that of the regression on grouped variables. The resulting integrated models also have the highest R_a^2 and lowest SEE values indicating that these are the best-fit models for the target species. The regression statistics of the best-fit integrated models are given in Table 3.9.

Model 9, which is the best predictor model for *P. falcataria,* suggests that in the study area site index is limited by the ecological factors WI, SR, and RAIN. It can predict as much as 58% of the site index variation with SEE=1.256. In this model, RAIN has the greatest impact on site index (SRC=0.587) and the addition of this variable reduces the model sum of squares error by 51%.

In the case of *E. peltatum,* the best performing model (Model 10) includes E, WI, SR and RAIN variables. The model accountability is the highest among all species with R_a^2=0.609 and SEE= 3.677. From among the ecological variables selected in the model, RAIN affects site index the most having an SRC value of 0.382 and can reduce SEE by as much as 23%.

Table 3.9 Regression statistics of the best-fit integrated models for each target species

Model No.	Species	Ecological Variable	p-value	SRC	PCD	VIF
9	a	WI	0.000	0.192	0.083	1.147
		SR	0.000	-0.203	0.120	1.100
		RAIN	0.000	0.587	0.507	1.045
10	b	E	0.000	-0.463	0.252	1.647
		WI	0.038	0.096	0.018	1.278
		SR	0.005	-0.124	0.034	1.130
		RAIN	0.000	0.382	0.229	1.275
11	c	E	0.000	-0.480	0.262	1.057
		SR	0.012	-0.296	0.119	1.057
12	d	E	0.050	-0.178	0.051	1.294
		SD	0.005	-0.239	0.107	1.037
		RAIN	0.000	0.592	0.377	1.261

Species letters a,b,c,d correspond to the the following : a = P. falcataria, b = E. peltatum, c = A. mangium, d = G. arborea; SRC= Standard regression coefficients, PCD= partial coefficient of determination, VIF= variance inflation factor

Model 11, which is the best-fit model selected for *A. mangium,* comprised of E and SR as the most significant predictor variables. It can predict about 36% of the variation in site index and has an error of 3.615. Between the two variables, E has the higher SRC and PCD values, which is equal to 0.480 and 0.262, respectively.

Finally, Model 12 exhibited the highest values among all models tested for *G. arborea*. The independent variables selected in the model are E, SD, and RAIN, which in combination could take into account as much as 52% of site index variability with an error of 1.969. Similar to the results of the other three species, the variation in RAIN variable has the largest impact on site index with SRC = 0.592 and CPD=0.377.

Table 3.10 Form of the common variable site index models for each target species

Model No.	Species	Equation	p-value	Adj. R^2	SEE
13	a	SI = 24.885 – 0.030 (E)	0.000	0.161	1.776
14	b	SI = 56.191 – 0.194 (E)	0.000	0.490	4.196
15	c	SI = 29.872 – 0.134 (E)	0.000	0.287	3.813
16	d	SI = 25.672 – 0.050 (E)	0.000	0.220	2.514

Species letters a,b,c,d correspond to the following: a = P. falcataria, b = E. peltatum, c = A. mangium, d= G. arborea

Among the significant models, a common variable model was selected to estimate site index variation in the plantation area. Single variable models using RAIN and E tested significant for all species, and the form of the model corresponds to Model 8 and Model 1 in Table 3.7. The regression statistics of Model 8 show better performance than Model 1 particularly for *P. falcataria* and *G. arborea*. However, Model 1, using the elevation variable, was chosen over Model 8 as the best common variable model. The site index equations using the common variable E for all species are given in Table 3.10. The common variable models have an accountabilities ranging from 16-49% which are lower than the accountability observed from best-fit models.

The site index predicted values using the best-fit models for each species were generally in a 1:1 relationship with the measured site index values of the sample plots (Figure 3.1). The selected models were further tested using data from the validation plots (Figure 3.2). A bigger range of errors is observed for *E. peltatum* and *A. mangium* as compared to the other two species. The errors from the validation analysis are generally not biased and show no trend, but as expected, models performed better in the sample than in the validation plots. In the case of *G. arborea*, a slight negative bias is observed but these may due to the limited distribution of validation plots for this species.

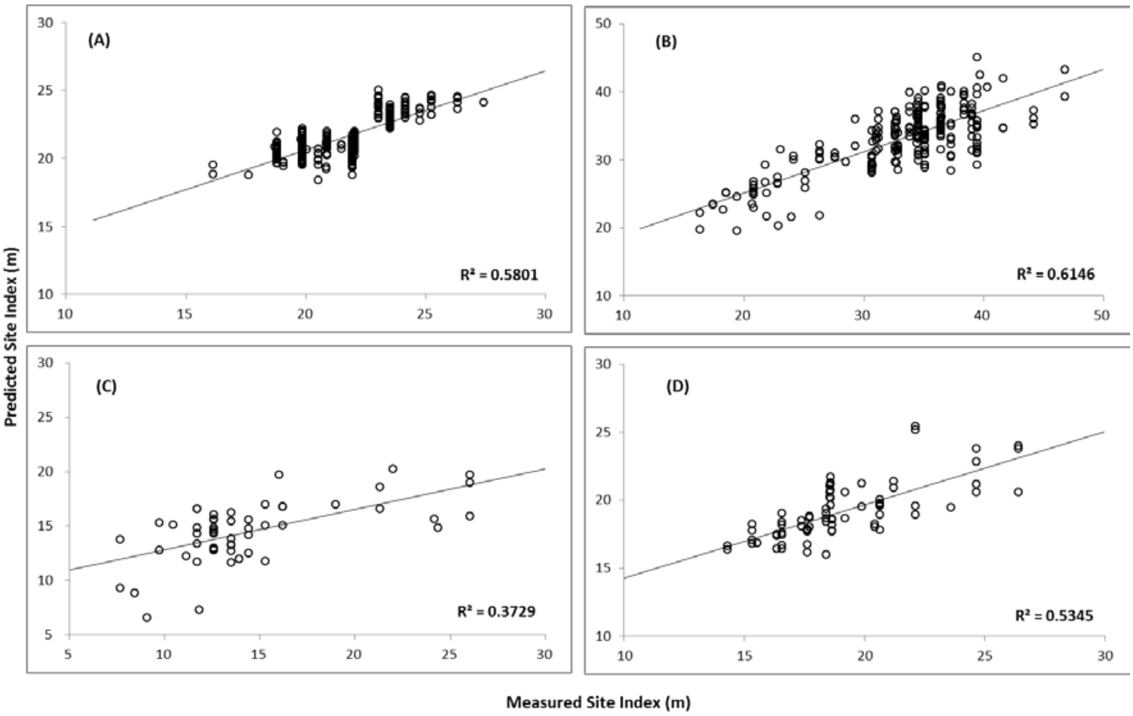

Figure 3.1 Comparison of measured and predicted site index values for (A) *P. falcataria*, (B) *E. peltatum*, (C) *A. mangium*, (D) *G. arborea* using best-fit integrated models

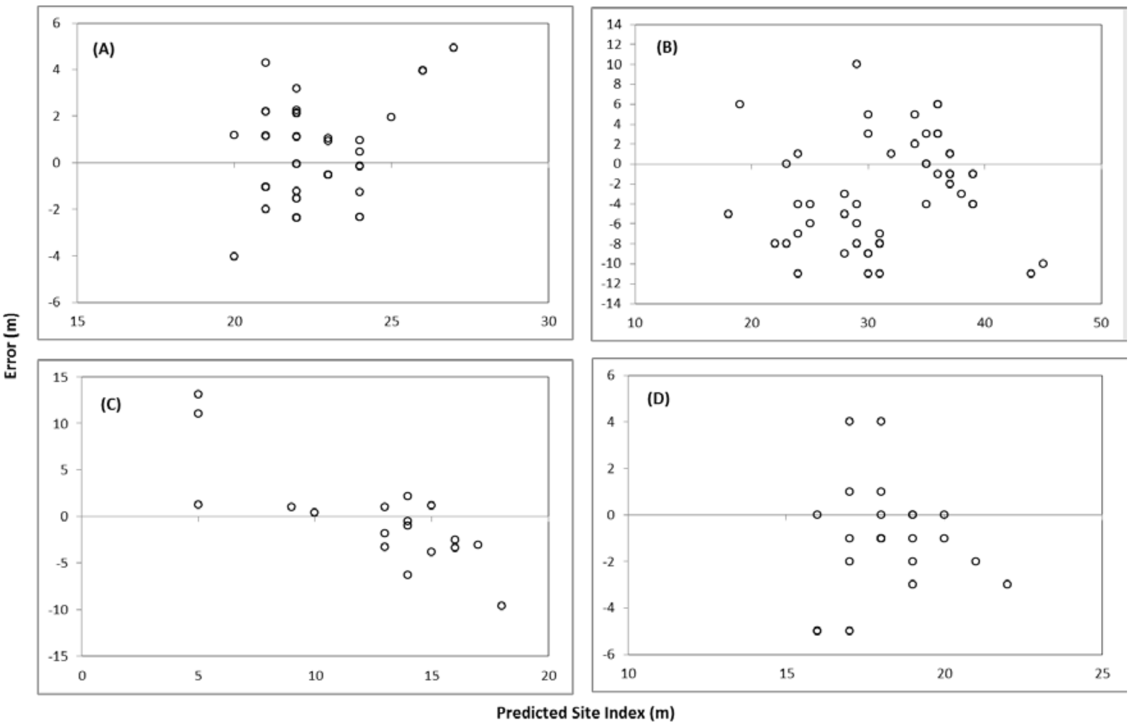

Figure 3.2 Mean error from predicted site index on validation plots for (A) *P. falcataria*, (B) *E. peltatum*, (C) *A. mangium*, (D) *G. arborea* using best-fit integrated models

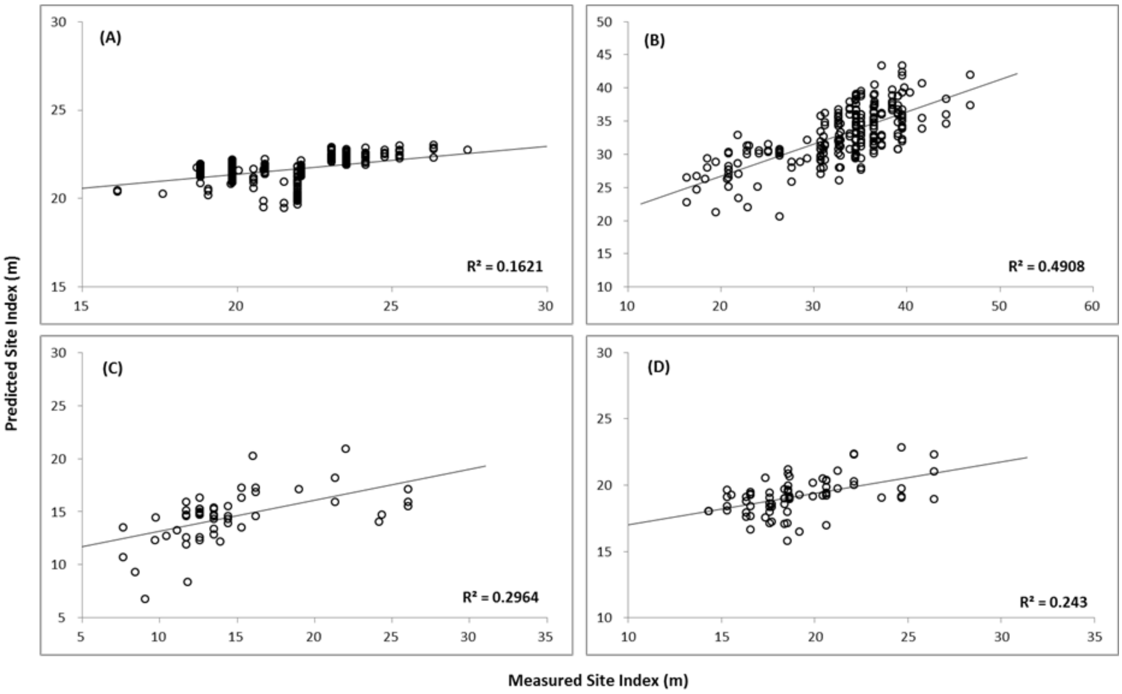

Figure 3.3 Comparison of measured and predicted site index values for (A) *P. falcataria*, (B) *E. peltatum*, (C) *A. mangium*, (D) *G. arborea* using common variable models

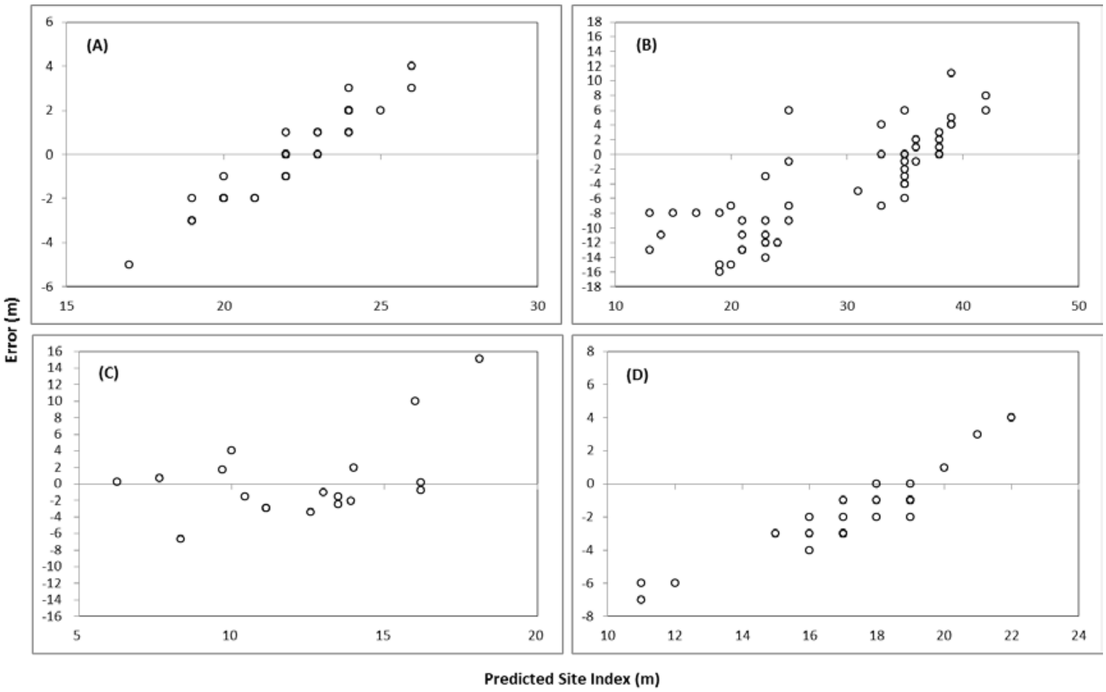

Figure 3.4 Mean error from predicted site index on validation plots for (A) *P. falcataria*, (B) *E. peltatum*, (C) *A. mangium* and (D) *G. arborea* using common variable model

Similarly, the predicted site index values using the common variable models for each species were generally in a 1:1 relationship with the measured site index values of the sample plots except for some stray values (Figure 3.3). In terms of validation, errors were observed to be bigger from the common variable models than the best-fit models due to the lower accountability observed from the former (Figure 3.4).

In order to determine the spatial distribution of site productivity in the study area, the selected predictor models resulting from the regression analysis were paired with weighted sum overlay analysis. The beta coefficients of the ecological variables in the regression models were used as weights in order to come up with raster maps showing the distribution of site productivity for the target species. Figure 3.5 shows the range of site productivity supported by the study area with respect to the target tree species using the best fit model. Focusing on the production areas which correspond to the plantations, maps showing the mean estimated site index and spatial variability across the plantation blocks were also developed. These maps were developed using the best-fit models (Figure 3.6) and common variable models (Figure 3.7). Comparing the mean predicted site index estimates from the two models revealed that for all species the site index estimates from the common variable model are generally lower than the best-fit models. The comparison also shows a generally 1:1 correlation between the two models (Figure 3.8), particularly for *E. peltatum* (r=0.82) and *G. arborea* (r=0.50). A lower correlation is observed for *A. mangium* (r=0.28) and *P. falcataria* (r=0.20).

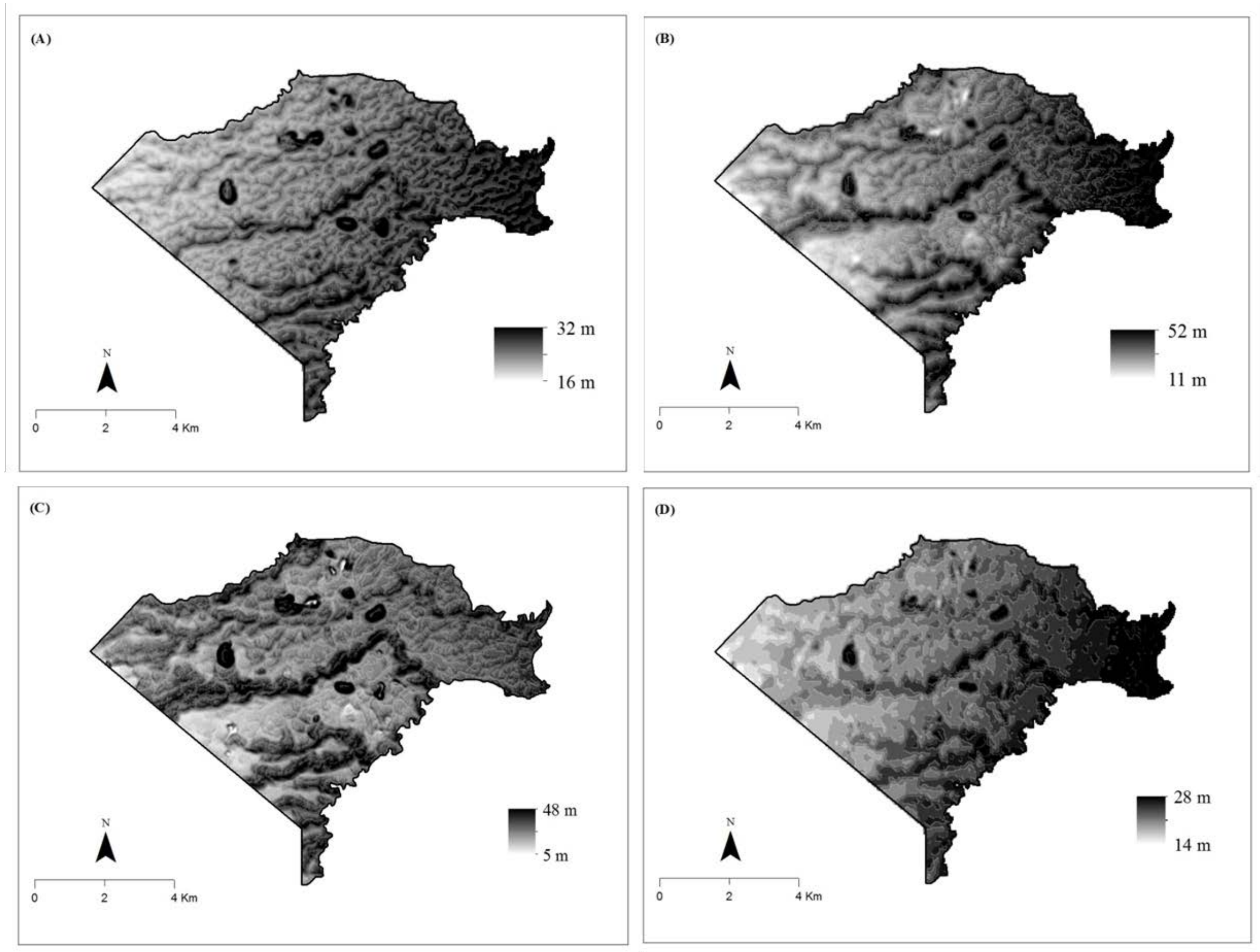

Figure 3.5 Raster maps showing site index variability across the study area for (A) *P. falcataria*, (B) *E. peltatum*, (C) *A. mangium* and (D) *G. arborea* using the best-fit integrated models

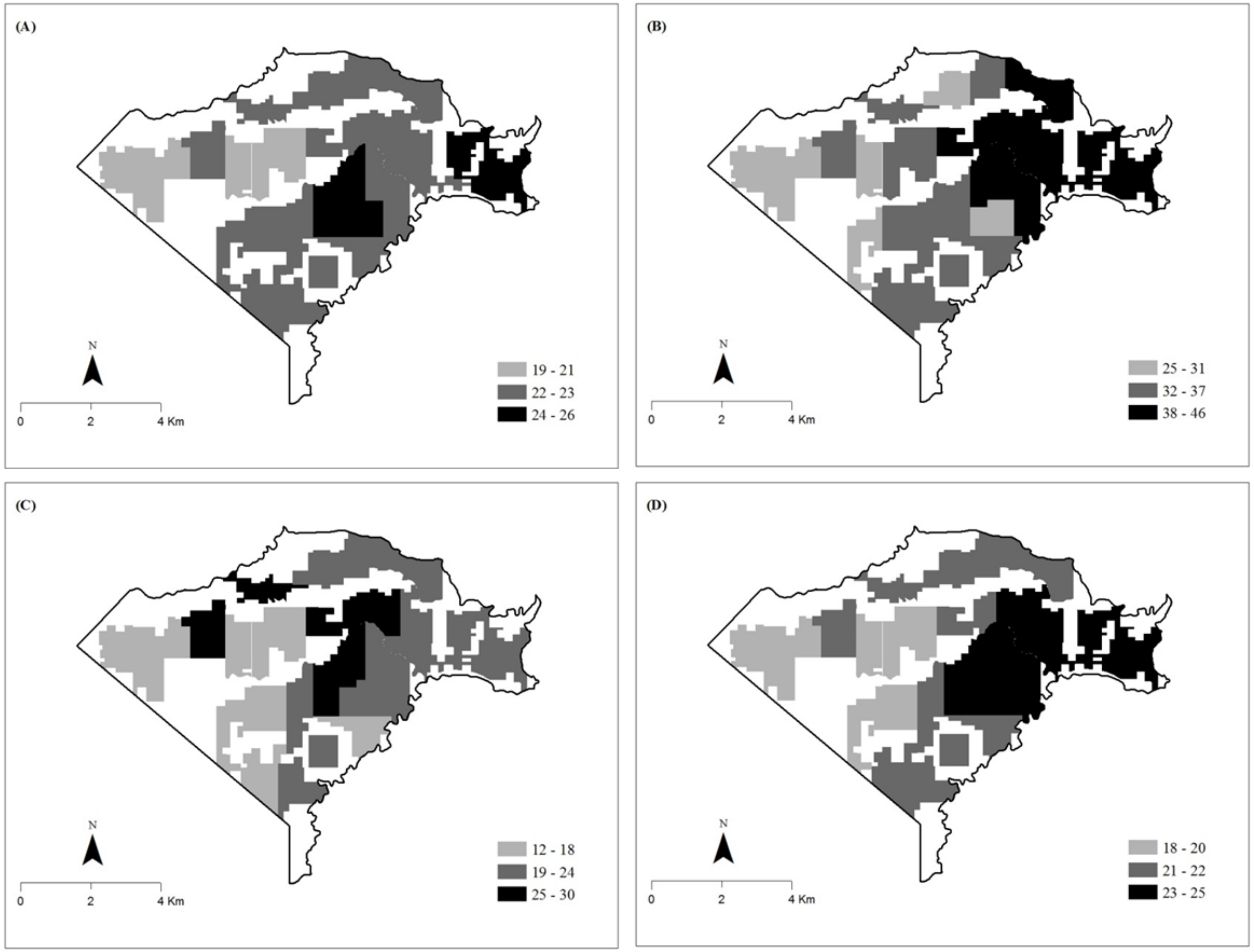

Figure 3.6 Site index maps showing mean predicted site index and variability across the plantation areas for (A) *P. falcataria*, (B) *E. peltatum*, (C) *A. mangium* and (D) *G. arborea* using the best-fit integrated models

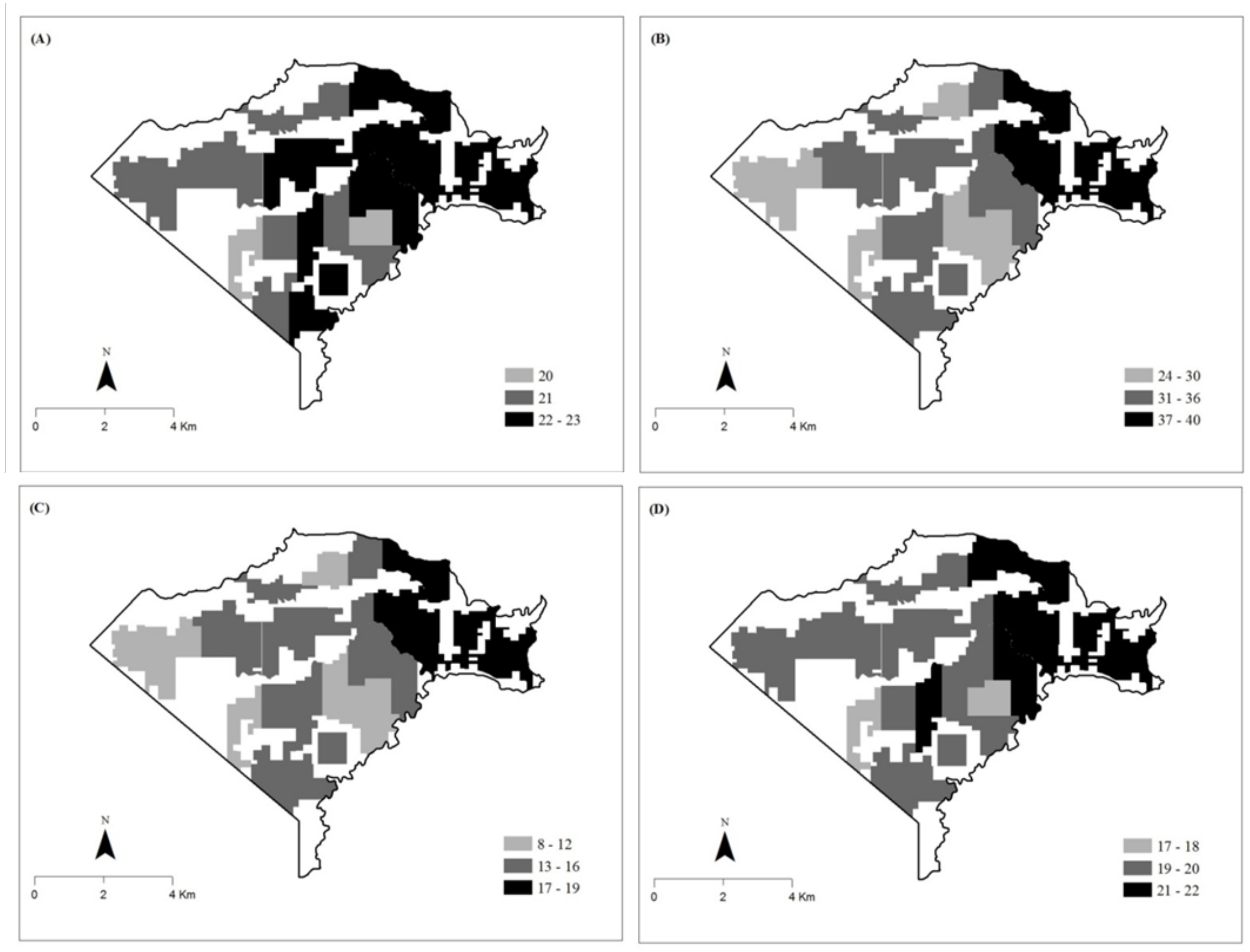

Figure 3.7 Site index maps showing mean predicted site index and variability across the plantation areas for (A) *P. falcataria*, (B) *E. peltatum*, (C) *A. mangium* and (D) *G. arborea* using the common variable models

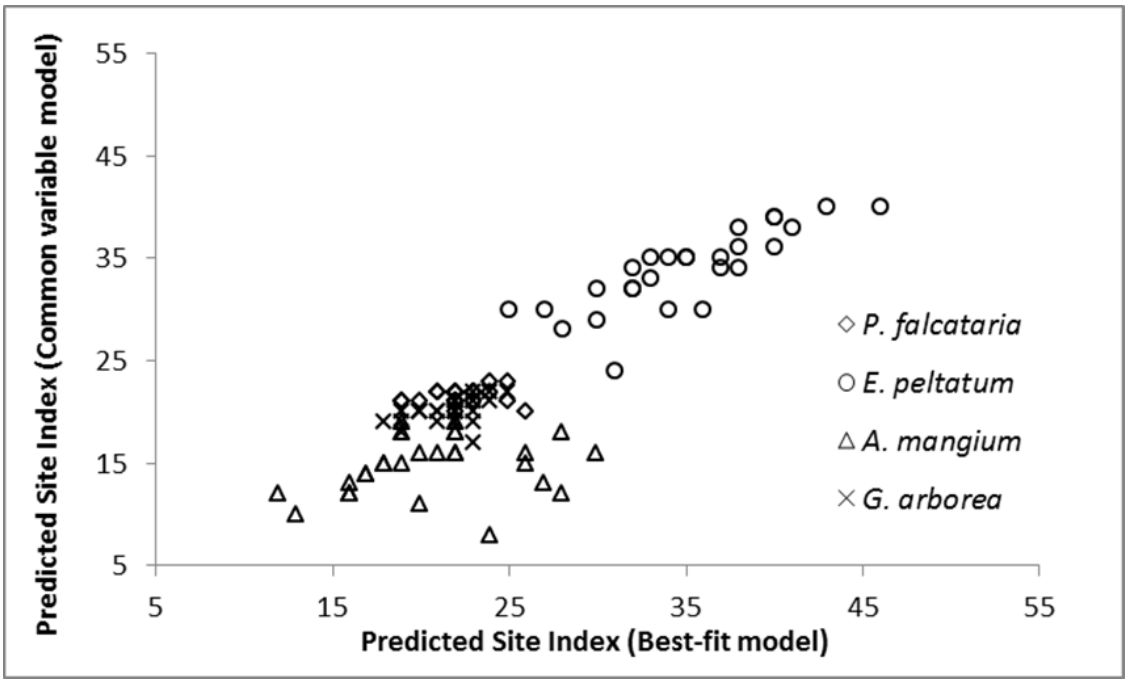

Figure 3.8 Comparison of mean predicted site index values for the target species in the plantation areas using the best-fit and common variable models

2.3 Discussion

Regression analyses between site index and ecological factors were performed to model spatial variations in the site indices of four major industrial tree plantation species in the Philippines. The study also used the analytic approach in identifying the main ecological factors affecting the variability of site index of the target species. Ten independent variables grouped into four categories (topography, soil moisture, solar and wind and climate), and their combinations (integrated model) were tested. Studies relating ecological factors with site index of major plantation species are extremely scanty in the Philippines, so comparison of the results of the study was limited to the results of studies on other tree species.

2.3.1 Best species-specific site index predictor models

Among the four model groups tested for regression, climate models generally displayed the best prediction for *P. falcataria* and *A. mangium.* Adjusted R^2 values of the climate models for the two species are actually higher than the values reported in Farrelly *et al*. (2011), Fontes *et al*. (2003), Wang and Klinka (1996), Ercanli *et al*. (2008), with values 0.28, 0.31, 0.02 and 0.295, respectively. The performance of the climate models for *E. peltatum* and *G. arborea* may be low relative to the two other species, but the values are still higher than the values reported from above-mentioned studies. Topography models are commonly used in site-site index correlation studies and results of this study show that topography was able to model site index variation of *E. peltatum* by ~50%. These values are higher than the limits reported in Mitsuda *et al*. (2001) where topography models displayed a predictive power of 0.28-0.31 only. On the contrary, results obtained in the study are lower compared to the estimates of Chen *et al*. (1998) where elevation, aspect, and slope position factors predicted 60% of trembling aspen site index. In addition, studies of Seynave *et al*. (2005), Socha (2008), and Ercanli *et al.* (2008) reported higher performance of topography models, particularly elevation, explaining about 49-66% of variation in spruce site index. The differences in the performance of climate and topography models from this study compared with other studies may arise from species and geographic variation. The effects of topography and climate may be less or more pronounced depending on the species and geographic location.

Models related to soil moisture and exposure to sun and wind performed poorly (5-22%) in this study. This is relatively lower than the values reported in Mitsuda *et al.* (2007), which also used DEM-derived variables to model soil moisture and site exposure to sun and wind using different DEM resolutions. High predictive values range from 45-62 % using DEM scales 12.5 m and 50 m while low values using DEM with a resolution of 25 m and 100 m range from 15-31%. Zhang and Montgomery (1994) and Mitsuda *et al.* (2007) suggested that fine resolution DEM is necessary to model soil-water dynamics indicating that the coarse resolution of the map used in the study may have partly contributed to the poor performance of the models.

2.3.2 Main ecological factors affecting site productivity

Across the target species, best-fit models included different combinations of ecological variables. This indicates that site quality of plantation tree species is controlled not only by an individual ecological factor but also by a combination of factors (Chen and Abe, 1999; Ercanli *et al.*, 2008). Based from the predictor model selected for *P. falcataria,* its site index is severely limited by the wetness index, exposure to direct solar radiation and amount of rainfall received by an area. Based on the results, *P. falcataria* prefers areas with high soil moisture located near valleys and river beds with lower exposure to direct sunlight and receives high amount of rainfall. Owing to the high evapotranspiration nature of *P. falcataria* (Krisnawati *et al.*, 2011), its productivity decreases when high exposure to sun increases soil temperature and consequently increasing evapotranspiration. In the case of *E. peltatum*, variables elevation, wetness index, direct solar radiation and rainfall are greatly associated with site index variations. Higher productivity for this species could be achieved in areas with lower elevation and approaching water pathways. Growth is also perceived to be favorable in areas, which are not too exposed to sunlight and receives ample rainfall throughout the year. With regards to *A. mangium,* the limiting factors are site altitude and the amount of direct solar radiation. Site index is high in lower elevation and in areas with lower exposure to direct sunlight. The site index of *G. arborea* is limited by the following site factors: elevation, sunlight duration, and rain. High site productivity is expected from areas of lower elevation, which receives a high amount of rainfall and with shorter sunlight exposure. A study of Vanclay *et al*. (2008) in Leyte Province Philippines looked into the relationship between site index of *G. arborea* and the physical environment. The resulting model included soil depth and slope explaining about 15% of the site index variability. The predictor model developed in this study did not include slope as a significant predictor variable for *G. arborea* but it has a higher prediction power of 52%.

2.3.3 Common variable model for multi-species plantation

The best-fit models selected for the target species differ in the set of ecological variables included in the model. This finding is rather usual as different species require varying sets of site factors to achieve optimum growth. However, in the context of mixed plantation or even multi-species plantation, it is desirable to have a common set of variables on which the predictor models will build upon. Although the common variable model using the rain variable has a generally better performance, the elevation model was selected because, (1) it is more practical and available as elevation can be easily derived from DEM as compared to rainfall, and (2) it is more stable, as elevation is not as vulnerable as rainfall to changes over time. The common variable models though with lower level of accountabilities as compared with the best-fit models could reliably predict the mean site index of the plantation blocks in the study area. It gives a parallel ground in comparing the site productivity for different species. In addition, when combined with other information like yield and rotation ages, the common variable model becomes an essential tool in prioritizing species for a given site in order to achieve optimum productivity levels.

2.3.4 Spatially-referenced site productivity map

The best-fit and common variable models give a numerical estimate of the area's site productivity, but the developed raster maps give a visual idea of the probable distribution of the variation in site index. The full potential of species-specific site index models can be achieved if it is combined with actual maps showing the ground location of areas with low and high site productivity. The maps show the variation of site index across the study area for all species. The variation appears to be at the highest with *E. peltatum* and lowest with *P. falcataria*. However, the site index variation for each species are not directly comparable with each other in the sense that a site index value of 50 for *E. peltatum* is not the same as the site index value of 50 for *P. falcataria* or other species. This is because they exhibit different growth patterns and site index were estimated using different base ages.

2.3.5 Model scope and limitations

Several studies on modeling site index with site factors included soil and soil characteristics. These factors were not considered in the study. Soil variables were not included due to the following reasons (1) the objective is to model site index from easily measured and available ecological factors, and 2) the species targeted in the study are mostly well-adapted to a wide range of soil types and can grow well even on degraded sites. Although this study did not use soil and soil-related variables, the resulting models showed good predicting power using ecological factors other than soil. The performance of the models resulting from this study is comparable to the predicting power (23-81%) reported for models using soil variables (Carter and Klinka, 1990; Wang and Klinka, 1996; Chen *et al.*, 1998; Corona *et al.*, 1998; Curt *et al.*, 2001; Chen *et al.*, 2002; Fontes *et al.*, 2003; Seynave *et al.*, 2005; Louw and Scholes, 2006; Ercanli *et al.*, 2008; Socha, 2008; Farrelly *et al.*, 2011). Combining soil variables with the models used in the study may further improve the accountability of the developed species-specific models.

Farrelly *et al.* (2011) stated that species-specific site index models to be useful must be able to explain at least 50% of the variation in site index. Best-fit models for *P. falcataria*, *E. peltatum*, and *G. arborea* successfully meet this criterion except for *A. mangium*, which missed the limit at 36%. In spite of the good performance exhibited by the best-fit models, still a portion of site index variation (39-64%) could not be explained by the models. Errors in site index estimation using ecological variables may be due to several reasons (Curt *et al.*, 2001; Fontes *et al.*, 2003; Bosela *et al.*, 2013): (1) errors in sampling and field surveys, (2) non-inclusion of consistent descriptor of site index variation, (3) inadequate sampling of the ecological complexity of the study area, (4) genetic variation, (5) former land use and silviculture. In the case of the study, major possible sources of poor correlation may be genetic variation particularly for the introduced species and the failed attempt to model over-all complexity and variation of ecological factors using DEM data. The highly introduced species in the area, though well-adapted to a wide range of site characteristics, pose a problem when the provenances are not ascertained and determined. Another possible source of error is the limitation associated with the ecological factors considered in the study particularly the climatic variable. Model improvement could be achieved by the inclusion of samples covering a wide range of possible and more accurate values for each ecological factor. Moreover, using a finer-scale and resolution DEM data may help bring out a more truthful variation in the calculation of ecological variables used in the study. Moreover, the realibility of the site index estimates also depend on the site index equations used to determine measured site index values during model development. In order to increase accuracy of the models, the use of stem analysis method in determining site index of trees or stands for model development should also be explored.

Due to the limited scale from which this study was conducted it may be difficult to provide a complete description of the site factors affecting the growth of the target species. However, the models substantially describe the factors affecting species productivity in the study area and in areas with similar characteristics where these species are intensively grown for commercial purposes. Studies relating site factors to site productivity are lacking in the Philippines, and usually site quality estimation is anchored on results of small-scale species trials. The results of the study provide significant contribution in narrowing this knowledge gap and consequently in improving the management of industrial tree plantations.

2.4 Conclusion

In the Philippines, species-site matching is not appropriately implemented because of the severe lack of knowledge on spatial variation in site productivity of areas allocated for reforestation and plantation development. Knowledge of species-specific site productivity is important in forest management, and the lack of it is usually one of the culprits behind failed reforestation attempts and poor growth and production in plantations. This study sought to address this problem by developing site index estimation models using ecological factors for major plantation species namely, *P. falcataria*, *E. peltatum*, *A. mangium*, and *G. arborea*. The highest model accountability was observed from the lone native species, *E. peltatum*, followed by *P. falcataria*, *G. arborea* and *A. mangium.* The best fit models selected for each species were able to explain as much as 36-61% of site index variation, making them fit for application in the study area. The models indicated that different site factors limit the productivity of each species, which justifies the importance of species-specific site index models. A common variable model was also developed to facilitate prioritization among multiple species on plantation areas to achieve optimum productivity levels.

The target species are described to be widely adapted so it is possible that in other areas other ecological factors may be found significant for predicting their site indices. The results in this study were derived from a small-scale area and models could be further improved if values from a larger scale will be considered. The application of the models should be limited to the site and conditions considered in model development.

The results of the study provide baseline information on the site productivity of the study area where productivity is previously unknown and in estimating site index in areas where the target tree species trees are currently non-existent. The study also demonstrated the potential of using a practical yet scientific approach in determining site productivity for plantation species in the Philippines. These will serve as practical and valuable tools for forest managers by reducing the need for costly and time-consuming ‘trial-and-error” methods in identifying what tree species are suitable to the site. They can also provide insight to help forest managers in making future decisions related to the sustainable management of forest plantations.

Chapter 4
Stand level assessment of factors affecting the probability of wind damage on industrial tree plantations

4.1 Introduction

Forest plantation management usually encounters a multitude of challenges and risks making the development of management plans difficult and complicated. It is often difficult and sometimes impossible to address all these challenges and risks, so usually forest managers take into account only those which affect the plantation at a greater degree. One of the most studied risks to plantations is wind throw or wind damage.

Wind damage to plantations either happen regularly or during events of wind disturbance like wind gusts, tornadoes, hurricanes, storms, and typhoons. These events represent an important natural disturbance process to tropical and temperate forests (Boose *et al*., 1994). During wind disturbances, trees may be overturned, or crown and stems may break. Schindler *et al.* (2012) noted that the damage resulting from high-impact winds of large intensive depressions may be catastrophic and inflict substantial ecological, social and economic impacts. Further, Rich *et al.* (2007) added that damages could result to leveling of forest stands, change in forest structure, alteration in species composition and shift of resources spatially and temporally. These statements were supplemented by other studies who related that damage to forests and plantations may also range from loss of high-value timber, increased harvesting costs, reduced production among older trees, increased susceptibility to pests and diseases and disruption of silvicultural and management plans (Mitchell, 1995; Valinger and Fridman, 1999).

According to Mitchell (2012), forest managers particularly those in forested regions where wind damage occurs frequently should be careful not to ignore but instead embrace it as a natural disturbance process and make attempts to reduce its impacts. Merry *et al.* (2009) added that though the frequency of wind disturbance varies from year to year as well as its damage, it is crucial for forest managers to be prepared. In order to reduce the occurrence and severity of damage as well as economic losses, it is suggested that damage risk should be taken into account in managing forests and plantations (Valinger and Fridman, 1999; Jalkanen and Mattila, 2000) as well as understand what are the underlying site and management factors affecting susceptibility to damage (Nolet *et al*., 2012; Kamimura *et al*., 2013).

Wind damage probability models help forest managers understand how factors and their interactions could influence the site's vulnerability. These models could also form part of a decision support system to identify appropriate actions for high-risk sites. Perry and Wilson (2008) enumerated potential benefits of wind damage risk evaluation and these include, 1) evaluate where to locate plantations, 2) decide which regeneration strategies are appropriate, 3) determine the proper type and timing of silvicultural practices such as thinning and partial harvests and 4) determine what species composition or rotation length is desirable for individual sites.

Studies on wind damage conclude that the complex pattern of damage brought about by wind disturbance is a result of an interaction of meteorological, physiographic and biotic factors happening on a range of different spatial and temporal scales (Boose *et al.*, 1994; Mitchell, 1995; Valinger and Fridman, 1999; Rich *et al*., 2007; Perry and Wilson, 2008; Schindler *et al*., 2009; Schindler *et al*., 2012). More specifically, factors such as climate (maximum wind speed), topography (altitude, topographic exposure, slope, aspect), physical and biological stand attributes (age, diameter at breast height, total height, basal area, species composition, stand density) soil characteristics (soil type, deposit thickness, rooting depth) and silviculture (treatment history, timing of thinning and intensity) are identified as influential (Mitchell, 1995; Schindler *et al*., 2009).

The probability of wind damage is usually modeled using logistic regression analysis. Damage from severe wind disturbances are unexpected with usually heterogeneous effects in which non-normally distributed and normal regression approaches deem inappropriate (Dobbertin, 2002; Salmo *et al*., 2014). Several studies that modeled wind damage probability are of the empirical or mechanistic type (Dobbertin, 2002; Mickovski *et al*., 2005; Albrecht *et al*., 2012). Logistic models allow the estimation of probabilities that a certain discrete event will occur with respect to given independent variables. Using the estimated probabilities, a damaged or undamaged status can be determined for a forest stand (Dobbertin, 2002).

Empirical models use an observational approach (Mickovski *et al*., 2005) and associate damage with the stand, site and soil variables (Albrecht *et al*., 2012). These models provide general insights on the physical mechanisms of windthrow (Schindler *et al*., 2009) and use the available information to estimate the probability of damage occurrence without prior knowledge of the underlying processes (Dobbertin, 2002). In actuality, these type of model provides a quantitative description of the circumstances of the damage (Albrecht *et al*., 2012).

On the other hand, mechanistic models consider both tree and stand characteristics as well as wind characteristics of the site. It involves an analysis of modeled airflow systems and allows the investigation of the physics behind tree failure and mechanisms of storm damage in general (Albrecht *et al*., 2012). A popular and widely-used example of a mechanistic wind damage model is GALES that estimates the threshold wind speeds required for overturning and breaking the mean tree of the stand. (Mickovski *et al*., 2005).

Mechanistic models for predicting wind damage probability are gaining ground over empirical models because of their greater determination capacity. Unfortunately, its applicability in the study area is limited by the lack of information on factors like near-surface airflow, soil types, and others. The study, therefore, focuses on the development of an empirical wind damage model. Empirical methods encompass different techniques and different spatial scales (Albrecht *et al*., 2012). Traditionally, wind damage to forests has been studied based on inventories in the damaged areas or in field experiments (Valinger and Fridman, 2011) but nowadays satellite imageries are supplemented with ground surveys to assess the extent of damage. Usually, storm damage is usually analyzed for one specific storm event (Boose *et al*., 1994; Canham *et al*., 2001; Brundl and Rickli, 2002; Schindler *et al*., 2009; Valinger and Fridman, 2011; Nolet *et al*., 2012; Albrecht *et al*., 2012) as it is often rare to have damage assessment data for the same area for different wind disturbance events. There are only a few studies which analyzed damage data from multiple wind disturbance events, and an example is the study of Dobbertin (2002).

The association between wind damage and stand and site conditions have been extensively studied in various regions in Europe, America and Japan but, unfortunately, not in Southeast Asia, particularly in the Philippines which is a typhoon prone country. On the average, the Philippines is frequented by around 20 tropical typhoons per year

(Stromberg *et al*., 2011). A number of global climate models projected a likely increase in the intensity of tropical cyclones (Stromberg *et al.*, 2011) which implies that damage from strong winds and rain accompanying storms and typhoon may also increase (Kamimura *et al*., 2013). In the Philippines, the 60-year storm data shows no significant trend in the frequency of tropical cyclones forming or entering the country's area of responsibility (Stromberg *et al*., 2011; Yumul *et al*., 2012). However, the last few years indicate a relative increase in the intensity of typhoons and this apparent trend may be attributed to climate change particularly to the increase in sea-surface temperatures.

From a country that is frequently visited and battered by storms and typhoons it might be expected that the extent of damage is periodically evaluated and monitored. Unfortunately, Philippines seem to lag behind in this aspect. Israel and Briones (2012) attempted to quantitatively and qualitatively analyze the impacts of natural disasters such as typhoons, floods and droughts on agriculture, food security and natural resources and environment in the Philippines. Results of the study show that most of the available literature quantifying damage and evaluating risk are focused on agricultural crops and at the moment studies which quantitatively measure the impacts on forests and other vegetation are lacking. However, they also concluded that there is substantial evidence that natural resources and environment sector is affected by natural disasters. They stated that it was apparent that there is considerable damage to forest and plantations however the risks are not quantified and more so, not considered in management planning.

It is very likely that wind disturbances will continue to happen in the future implying that if risks to wind damage will be continually ignored, ecological and economic impacts on forest plantations may further exacerbate. This implies the importance of developing models or tools to predict wind damage probability, particularly in the Philippines that frequently experience wind disturbances and consequently damages. Hence, this study was developed. The objectives of the study are to (1) analyze the relationship between likelihood of wind damage and stand-level attributes, (2) develop a wind damage prediction model using multiple logistic regression analysis, and (3) develop a wind damage risk map.

4.2. Methodology

4.2.1 Typhoon Bopha

The data on the path and wind speed and direction of typhoon Bopha were obtained from the website of Japan Meteorological Agency, which provides best track data for tropical cyclones in the western North Pacific and South China Sea. It was supplemented with information on the hurricane and its estimated destruction published on the website of National Aeronautics and Space Administration (NASA).

Typhoon Bopha was the 26th typhoon formed in the western North Pacific Ocean last November 25, 2012. From a tropical depression, Bopha rapidly intensified into a tropical storm and was classified as a full-blown category 5 typhoon in the Saffir-Simpson scale when it made landfall in the Philippine area of responsibility (PAR) in December 3, 2012. Moving in a west-northwest direction with maximum sustained winds of 50 mps and gustiness of up to 60 mps, Typhoon Bopha is considered as the strongest typhoon to have hit the Philippines in 2012. When it passed through Mindanao region, the study area was within the 140 km radius of the typhoon's strong winds whose speed is greater than 25 mps. The study area was approximately 60-70 kilometers away from the center of the typhoon whose maximum sustained winds were recorded at 45 mps. According to NASA (2012), as Typhoon Bopha moved out of PAR, high winds and heavy rainfall associated with it brought a death toll of 300 and severe destruction of homes and properties. Roughly about 80% of agricultural and forest plantations were destroyed when Typhoon Bopha wreaked havoc in the Mindanao region

4.2.2 Damage Data

Post-storm inventories of damaged plantation blocks were conducted in January and July, 2013 and included information on location, species, number of trees damaged and age. Areas identified as damaged through subjective visual assessment have at least 200 damaged trees per ha. The post-storm inventory data were overlain on the 2011 (before typhoon) inventory map of plantations to assess the general extent of damage. The overlay process showed that about 20% of the plantation area was damaged. A sample of undamaged blocks was randomly selected from blocks that are not identified as damaged in the post-storm inventory. The size of the blocks are relatively large (2-20 ha) to use for sampling and may not be effective in showing variations in and effects of terrain conditions. So the sample plots for each category (damaged and undamaged) were obtained by subdividing the corresponding blocks into smaller plots based on differences in elevation. Classification of sample plots were based on elevation because of the two terrain conditions considered, it appeared to be more variable. The resulting undamaged and damaged sample plots were then intersected with the site index maps resulting from the common variable predictor models from the previous chapter. The site index data from the intersection and age data from inventory were then combined to compute average stand height of each sample plot. The equations used for determining average stand height were derived from equations in Table 3.2 of the previous chapter.

4.2.3 Elevation and Topographic Exposure Index Data

The topographic site characteristics of sample plots, elevation and topographic exposure data were derived from the same digital elevation model (DEM) used in previous chapter. The estimates for each sample plot were then obtained by taking the average of the values within the plot.

Elevation and topographic exposure are the two most common topographic variables used in modeling wind damage probabilities. According to Ruel *et al.* (2002), the topographic exposure on a given site is equal to the sum of all vertical angles to the horizon in eight (8) basic directions to the cardinal points (N, NE, E, SE, S, SW, W, NW) . Topographic exposure factor is commonly used in evaluating threats of wind damage to forest stands, and is an important component of predicting site windiness (Quine and White, 1998).

In this study, topographic exposure index (TOPEX) was modeled using DEM and shaded topography. The works of Mikita and Klimanek (2010), Ying-kui (2013) and Batke *et al*., (2014) used the same methodology of creating topographic exposure factor in the GIS environment on the basis of digital elevation models and stated that it may be modelled effectively using the hillshade tool. The hillshade algorithm which accounts for zenith angle, azimuth direction, slope and aspect determines shaded and illuminated cells which could be reclassified into exposed and protected cells. In this study, TOPEX was calculated using batch processing that enabled direct calculation of topographic exposure using elevation angle interval of 5^0 (0^0-90^0) and repeated for all azimuth directions from 0^0-360^0 for an interval of 10^0. The raster maps were reclassified into 0 and 1, where 0 raster cells represents protected sites and raster cells valued 1 are exposed areas. The resulting raster maps were added, and their sum is reduced to an index of 100, where increasing topographic exposure index value means increasing site exposure.

The works of Bell *et al*. (1995) proved that DEM could provide a fast and effective way of computing topographic exposure and allows complete coverage of calculations for the whole of upland Britain which is not possible through field measurements. It was further stated that the technique can be more reliable than field measurements as it is completely standardized and reproducible and reduces the possibility of human error both during the collection and analysis of data. This was further supported by the findings of Ruel *et al.* (2002), which reported that indices of wind exposure based on topographic features have been shown to correlate well with field measurements of average wind speed and also with wind tunnel results.

4.2.4 Stand-level factors

The stand level attributes used were average stand height (ASH), elevation (Elev) and topographic exposure index (TOPEX). Other studies on wind damage probability used age, diameter, basal area, site index and others to represent stand-related characteristics. In this study, only average stand height was used. Although stand age and estimated site index data are available for each sample plot, they were not considered as factors as they were already used in the computation of stand height implying some inter-relationship. Species composition was also not considered as a factor because information on species from post-storm inventory is limited to species identification with no information on species distribution or species proportion on each plot. Also, the study assumed a general description of even-aged stands of softwood species for all sample plots. Similarly, other factors such as slope and aspect were not included to represent topographic features of the sample plots because they were already included in the calculation of TOPEX. In terms of wind conditions, since only one typhoon event is considered in this study, the maximum wind speed (~45 mps) at the time when the study area is closest to the typhoon path was the assumed wind condition. Though, only these factors were tested, ASH, Elev, and TOPEX represent the most important factors used in determining a site's susceptibility to wind damage as identified in previous studies.

4.2.5 Statistical analysis

The study followed the process of logistic regression analysis to examine the association of wind damage probability and stand-level factors. In the analysis, damage occurrence (0,1) caused by the storm was the dependent variable and predictor variables included stand height to represent stand attribute and terrain conditions were represented in the form of elevation and topographic exposure index. Then, the expected probability of storm damage is described by using the logit transformation,

$$\mathrm{Logit}(P) = \ln(P/(1-P)) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n$$

From this relationship, the probability of wind damage (P) was calculated as,

$$P = \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n) / [1+\exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n)]$$

where X denotes predictor variables average height, elevation and topographic exposure index and β denotes coefficients. To fit the multiple logistic regression models, maximum likelihood estimation was applied for maximizing the probability. All statistical analyses were done using R (R Core Team, 2013).

Stand-level factors were subjected to univariate and multiple logistic regression analysis. Model fit was determined by the Hosmer-Lemeshow (H-L) goodness of fit, concordance statistic for discriminative ability or the area under the receiver operating characteristic curve (AUC) and Akaike Information Criterion (AIC). The H-L goodness of fit test is based on dividing the sample up into groups or profiles according to their predicted probabilities. The actual proportion of damaged plots in each group is then compared to the average predicted probability of damage for the group. The χ^2 (chi-square) values are then compared wherein a non-significant χ^2 value indicates a good model (Jalkanen and Mattila, 2000). On the other hand, Steyerberg *et al*. (2010) stated that the concordance statistics, which is a popular performance measure of generalized linear regression models, for binary outcomes is identical to AUC value. In this measure, each pair of observation is said to be concordant if the predicted probability of damage is higher for the plot that was actually damaged. It is similar to the coefficient of determination (R^2) in a normal regression analysis and can be interpreted as a derived index for the proportion of correctly classified events and non-events. AUC values range from 0.5 to 1, where a value of 0.5 and lower indicate that a model's predictive ability is no better than random chance. AUC values up to 0.7 are considered moderate, and values equal to 0.8 or higher indicate models can perfectly discriminate between events and non-events. Finally, models with lower AIC values indicate better fit of the model.

4.3 Results

4.3.1 Characteristics of damaged plots

A total of 84 (186 ha) damaged and 151 (237 ha) undamaged plots were used for the development of wind damage probability models. The summary characteristics of these plots with the corresponding stand-level attributes are given in Table 4.1. Undamaged plots have a mean age of 5 years, and the mean total height is about 15.2 m. The mean elevation and topographic exposure index of undamaged plots are 105 m and 92, respectively. In terms of damaged plots, a slightly higher mean age of 6 years is computed. The average height of the stand on damaged plots is also higher at 16.7. The mean elevation is 130 m, and topographic exposure index is 95.

Table 4.1 Summary of the damaged and undamaged plot characteristics used in the logistic regression analysis

Parameters	Undamaged Plots		Damaged Plots	
	Mean	Range	Mean	Range
No. of plots	151		84	
Age (years)	5	1-8	6	2-9
Average Stand Height (m)	15.2	5.3-23.2	16.7	9.7-24.9
Elevation (m)	105	38-187	128	88-182
Topographic exposure index	92	73-99	95	91-100

Figure 4.1 shows the proportion of damaged plots by each stand-level attribute used in the logistic regression analysis. Wind damage varies across different stand heights with a generally increasing proportion as average stand height increases. Similarly, the proportion of damaged plots increased with elevation and topographic exposure index. However, the proportion of damaged plots are limited on the range of 90-100 topographic exposure index values.

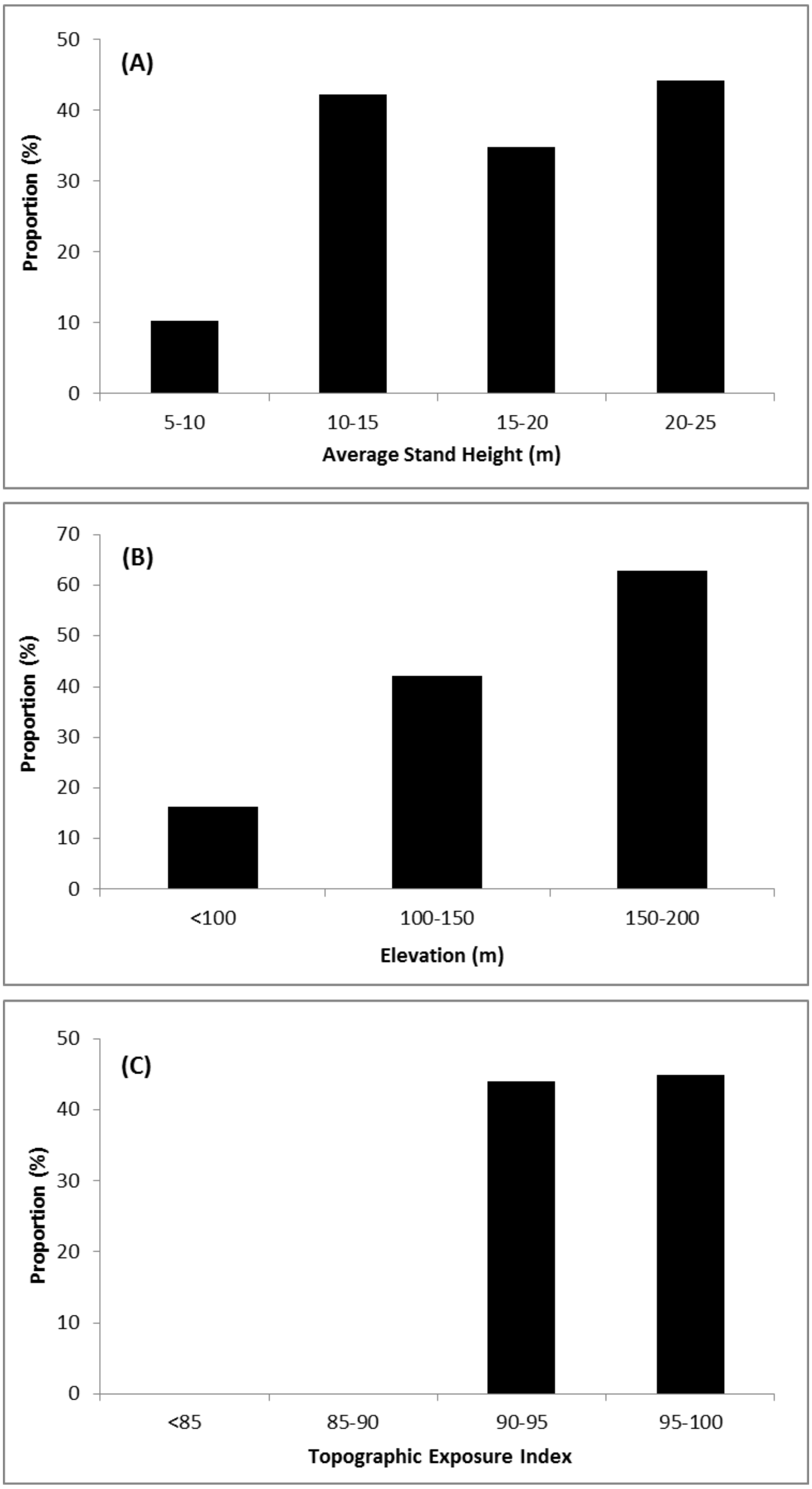

Figure 4.1 Proportion of damaged plots in the study area by (A) average stand height, (B) elevation, and (C) topographic exposure index

4.3.2 Correlation between stand-level variables

Pearson's simple correlation test was used to examine the degree of linear relationships between stand-level variables (Table 4.2). All correlation values are significant at α=0.01. A generally weak but significant linear relationship was observed between the stand-level variables tested. Average stand height is negatively correlated with both elevation and topographic exposure index. On the other hand, elevation is positively correlated with topographic exposure index.

Table 4.2 Correlation coefficients between stand-level variables

Variable 1	Variable 2	Correlation coefficient
ASH	Elev	-0.360
ASH	TOPEX	-0.391
Elev	TOPEX	0.473

4.3.3. Logistic regression analysis

All three stand-level factors were subjected to univariate and multiple logistic regression analysis (Table 4.3). The stand-level factors were all significant at the univariate level of analysis. Their combinations were also tested using multiple logistic regression analysis. The combinations of ASH with single stand-level topography predictors and combinations of topography predictors yield significant models.

Results of univariate analysis yield the highest AIC values and lowest AUC among the three model groups. The use of ASH as a single predictor variable has the lowest AUC value of 0.548 indicating the poor ability of the model in discriminating between damaged and undamaged plots. The use of stand-level topography variables as lone predictors are slightly better than the ASH model with AUC values ranging 0.674-0.718. Similarly, the combination of Elev and TOPEX in a single model performed better than the ASH model and its single topography variable counterparts. The highest AUC values were observed from the combination of the three variables in the multiple logistic regression analysis. The AUC value is 0.825 which meets the 0.80

limit value for perfectly discriminating models. With respect to the H-L goodness of fit test, the models which include Elev, Elev and TOPEX, ASH and Elev, and the combination of ASH, Elev and TOPEX have non-significant χ^2 statistic value. All others have significant χ^2 (p-value <0.05) indicating poor model fit for these models.

Table 4.3 Basic logistic regression models tested and their fit criterion values

Models	**Variables**	**AUC value**	**AIC value**	**H-L Test χ^2 statistic**	**H-L Test χ^2 statistic p-value**
Univariate	ASH	0.548	304.85	50.058	0.000
	Elev	0.718	278.9	12.655	0.178
	TOPEX	0.674	280.86	-	-
Topography	Elev, TOPEX	0.743	266.92	7.080	0.629
Combination	ASH, Elev	0.779	249.93	9.738	0.372
	ASH, TOPEX	0.765	261.96	30.113	0.000
	ASH, Elev, TOPEX	0.825	230.17	16.090	0.065

Based on values obtained for model fit criteria (AUC, AIC and H-L test), the occurrence of totally damaged plots was explained with higher accuracy by the multiple logistic regression model combining the three stand-level variables, ASH, Elev and TOPEX. The regression statistics of the best-fit model is given in Table 4.4. The beta coefficients for the three variables are all positive indicating that the probability of wind damage increases with a positive increase in any of these variables. The odds ratio for each variable could be interpreted as for an increase in 1 meter of average stand height, the probability of damage increases by 34%. In terms of a positive increase in elevation, the odds of being damaged are increased by about 4% and finally, for a change in the topographic exposure index, odds significantly increase by 26%.

Table 4.4 Regression statistics of the best-fit multiple logistic regression model

Variables	Coefficients	Standard Error	p-value	Odds ratio
Intercept	-31.065	5.541	0.000	-
ASH	0.292	0.061	0.000	1.339
Elev	0.038	0.007	0.000	1.038
TOPEX	0.228	0.055	0.000	1.256

4.3.4 Effect of average stand height

Using the maximum-likelihood parameter values, the effects of increasing average stand height were examined when values of topographic exposure and elevation are held constant (Figure 4.2). If topographic exposure index is relatively low (< 85), low and medium elevation areas have damage probabilities less than 50% even at an average stand height higher than 30 m. In the case of high elevation areas, the damage probability is higher than 50% beyond an average stand height of 27 m. An increase in the topographic exposure index value (85-90) would make areas with high elevation (150-200 m) susceptible to damage by more than 50% at an average stand height of 15 m. Meanwhile, medium elevation areas become are at risk of being damaged at a stand height higher than 22 m. At the same value of TOPEX, areas with elevation less than 100 m have higher probabilities of being undamaged than damaged even if the stand reach an average height of 30 m. Moving one TOPEX class (90-95) further, areas with elevation of 100-150 are already more than 50% vulnerable to wind damage if average stand height reaches 18 m while low elevation areas register more than 50% damage probability at 27 m average stand height. Areas at even higher elevations (>150 m) have high probabilities of damage even if average stand height is just about 11 m. Finally at the highest TOPEX class or in areas with very high exposure, high elevation areas are highly susceptible to damage even at a very low average stand height of about 7 m. In a similar manner, areas with an elevation of 100-150 m are already vulnerable if the height of the stands reaches 14 m. On the other hand, low elevation areas, only become susceptible to damage if the stands located in these areas reach about 24 m.

4.3.5 Model evaluation

A cross-validation was conducted in lieu of the absence of an independent data set to which the developed model could be tested. The cross-validation was done using the following approach: (1) the predicted probability was computed for each sample plot using the maximum-likelihood parameter values, (2) the entire data set was grouped into bins (0-0.1, 0.1-0.2, etc.) for a total of 10 bins and then computed the percentage of plots in the bin that had been damaged by the storm. The resulting value for each bin was then compared with the mean of the predicted probability computed for each bin. Basically, the method allows the comparison of "observed" and "predicted" probability values given the best fit model and shows the performance of the model across the whole range of probability values. Based on the evaluation, the best-fit model performs relatively well across the range of probability values (Figure 4.3). At some point, however, the graph shows that the model underestimates the probability between 30%-40% probability classes and slightly overestimates at 60%-70% probability classes. The method also allows the computation of R^2, and in this case a fairly high value (0.89) is obtained.

4.3.6 Wind damage risk map

Using the maximum likelihood parameter values of the best model, a risk map was developed to determine the high-risk and low-risk points in the study area (Figure 4.4). The potential risk to wind damage on each plantation compartment was projected for every 5 meter increase in average stand height (5-30 m). This was done to have an estimate of the critical stand height on which the plantation areas will have more than 50% probability of being damaged. Based on their topographic characteristic (elevation and topographic exposure), 15% of the plantation blocks are at high-risk of being damaged when stands are grown at a height more than 10-15 meters. Medium-risk sites take about 81% of the whole plantation area and whose critical stand height is between 20 m. Finally, 7% of the area falls under low-risk category and stands on these sites could reach up to 25 m before they become susceptible to damage.

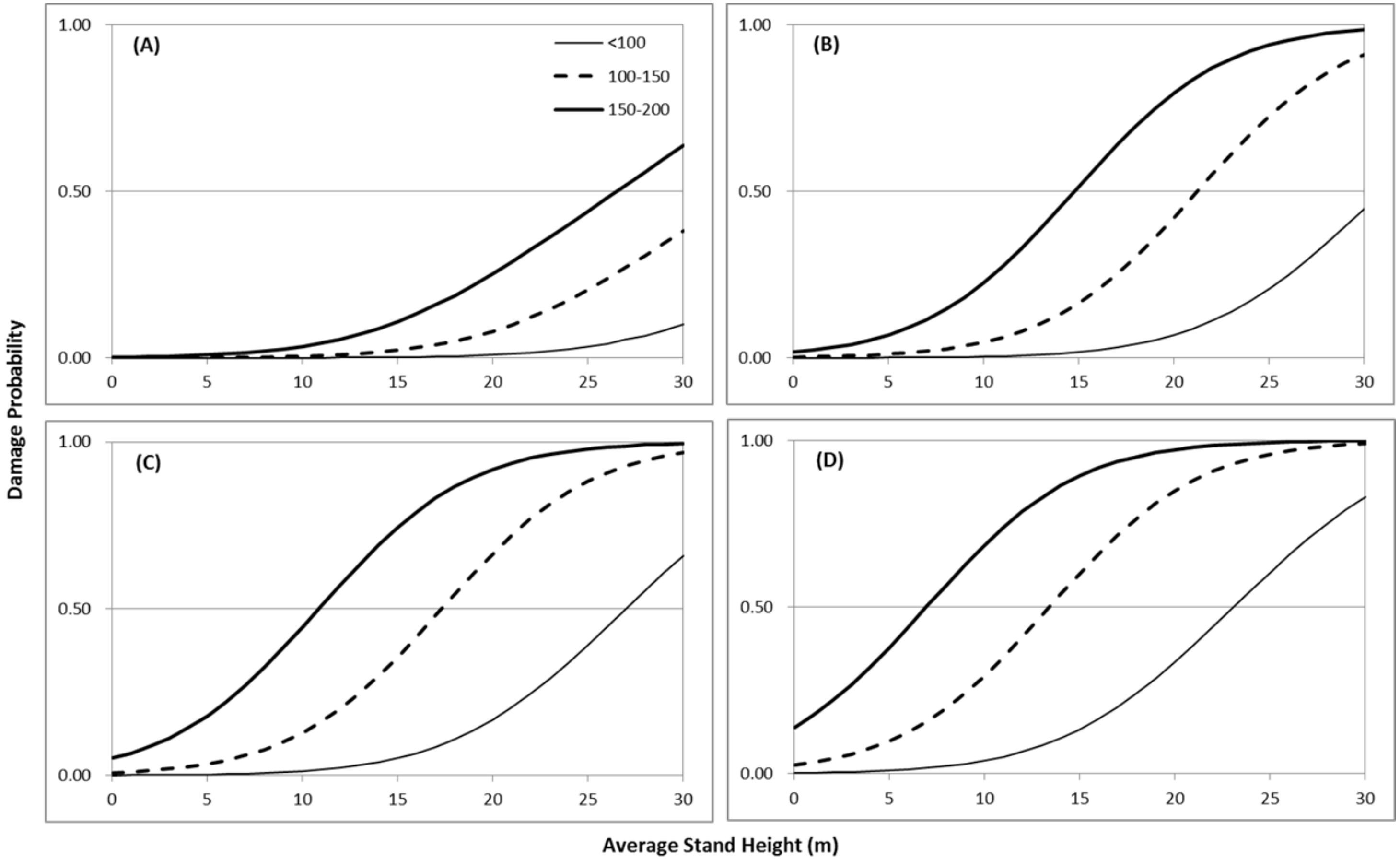

Figure 4.2 Effects of average stand height on wind damage probability when topographic exposure index and elevation factors are held constant, (A) TOPEX < 85, (B) TOPEX= 85-90, (C) TOPEX = 90-95, and (D) TOPEX=95-100. Thin lines indicate values for areas with elevation less than 100 m, broken lines indicate values for 100-150 m and bold lines indicate values for 150-200 m elevation.

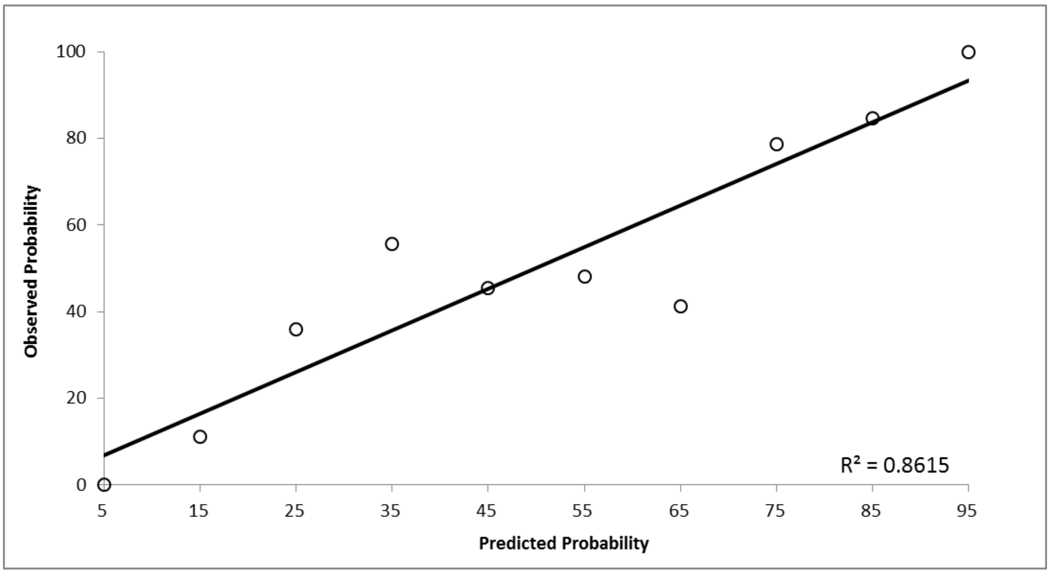

Figure 4.3 Predicted vs. observed probability of wind damage using best-fit multiple logistic regression model

4.4 Discussion

The study used the empirical approach to estimate the probability of wind damage to tree plantations that were severed during the 2012 typhoon event. Damage assessment on forests and tree plantations caused by natural disturbances like storms and typhoons are severely lacking in the Philippines. Ironically, the country is frequently visited by strong tropical storms and typhoon and periodically experiences destruction and severe damage from these disasters. The lack of reliable data from damage assessment equates to an ineffective and most likely failed implementation of a risk management plan.

4.4.1 Wind damage probability model

From limited data, the study attempted to model wind damage probability from available stand-level information like average stand height and DEM-derived site characteristics such as elevation and topographic exposure. Damage in this study is generalized as trees up thrown or with broken stems during the typhoon whose estimated maximum wind speed at the time of damage is about 45 mps. Based on

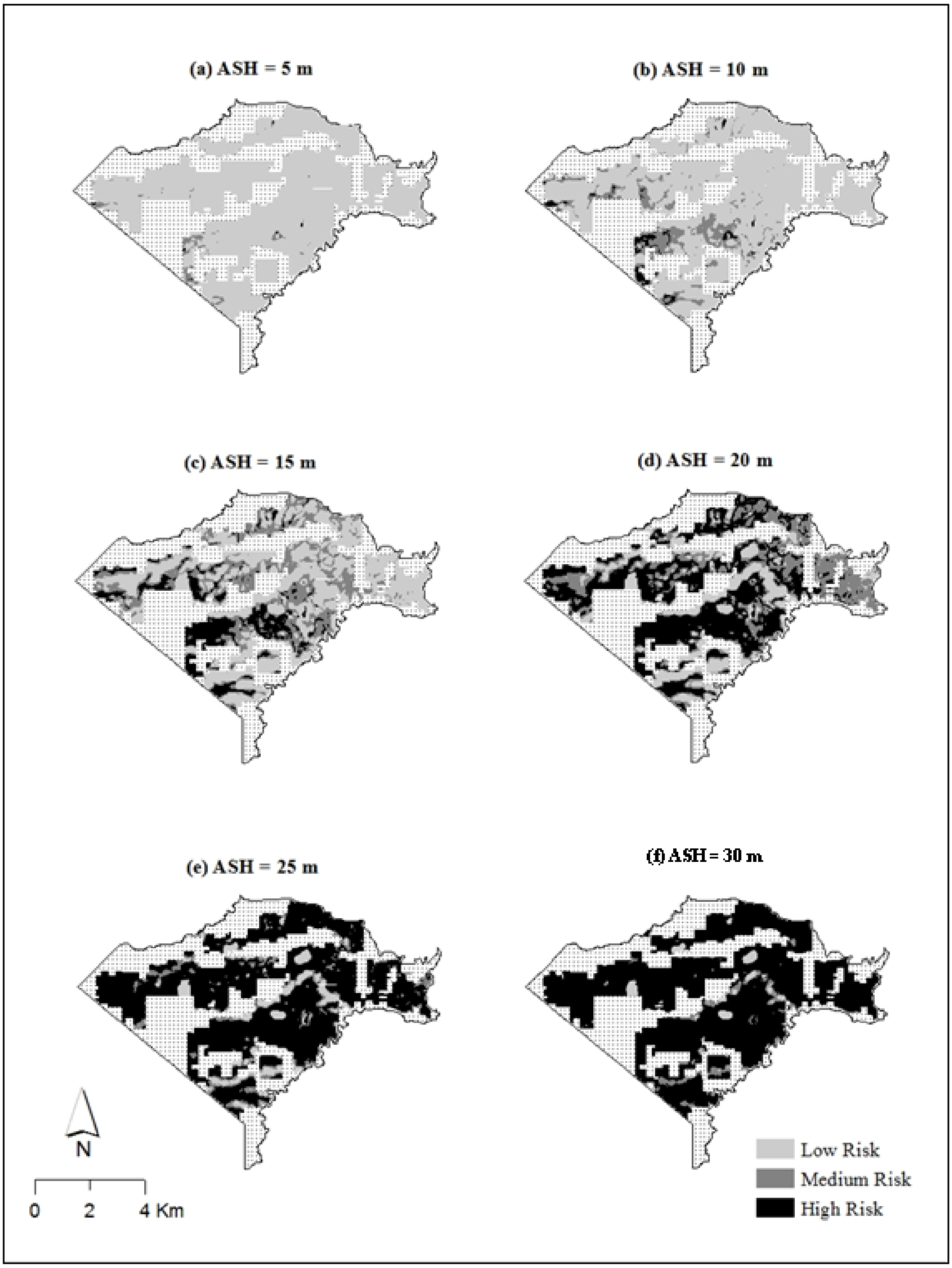

Figure 4.4 Wind damage risk maps of plantation areas with damage probability projections for average stand height increase from 5 m to 30 m

the results of previous studies on wind damage, it was hypothesized that the stand-level factors significantly influence the occurrence of wind damage on the plantation areas. The results of the logistic regression analysis affirmed this hypothesis.

The best fit model included all three variables tested as influential in determining a site's vulnerability to wind damage. The selected model has a high AUC value of 0.825 suggesting a good discriminatory power between damaged and undamaged areas. The evaluation of the model over the binned model data set also suggests a generally good performance across the whole range of probability classes.

4.4.2 Effects of key stand-level variables

The regression results on the best fit model indicate an increasing probability of damage with an increase in the stand-level variables. These findings conform to the general results reported by other studies (Valinger and Frindman, 2011; Tsuyuki *et al*., 2011; Ni Dhubhain *et al*., 2001; Dobbertin, 2002, and Albrecht *et al*., 2012). In particular, stand height is a typical stand characteristic considered in most empirical and mechanistic probability models. A generally increasing vulnerability is observed with an increasing height of the stand or tree. Tsuyuki *et al*. (2011) explained that taller trees or stands have greater tendencies to fall over at wind impact because they are less stable. Ni Dhubhain *et al*. (2001) related that though most studies generally agree on the positive effect of height on probability of damage, there are some cases where beyond certain heights the increase in vulnerability of stands to damage levels off. This may be attributed in part to a declining height/diameter ratio which renders a tree or plot more stable and less prone to windthrow. In addition, genetic characteristics of the species may also have been unaccounted for in explaining this trend. The results of the study showed that in the study area, taller stands are more prone to damage than stands with shorter trees. However, it must be noted that these plantations are short-rotation species grown for a period of 12-20 years. It may be possible that this observed effect has not captured the period at which the stands reach a decline in diameter-height ratio because they were already harvested. Also, the genetic properties and relative resistance of the species to wind damage have not been established and used in this study. Nonetheless, the model was able to explain the probable impact of stand height on a plantation managed under short-rotation periods.

Elevation and topographic exposure index variables which were used to represent the site characteristics in this study are also common variables used in probability models. Several studies identify wind exposure of the site as an important factor influencing the incidence of windthrow or damage (Ruel *et al.*, 2002; Merry *et al*., 2009). In fact, it is a critical variable, alongside elevation and wind zone, in the British windthrow hazard classification where topographic exposure accounts for more than 77% of the wind hazard rating system's total score (Quine and White, 1993; Ruel *et al.*, 2002; Perry and Wilson, 2008).

The best-fit model also identified elevation and site exposure as influential variables and show direct relationships with damage probability. This conforms to the findings of other studies which seems to all agree with the assumption that susceptibility increases in high altitude areas where exposure and wind speed are usually greater (Fridman and Valinger, 1998; Valinger and Fridman, 1999; Perry and Wilson, 2008; Merry *et al.*, 2009; Mitchell, 2012; Waldron *et al*.,2013; Batke *et al.*, 2014). Mitchell (2012) illustrated how wind funnels through and over terrain constrictions leading to areas of higher or lower mean flow and turbulence. In this case, ridges and valley gaps experience higher than average wind speeds.

The study focused on modeling wind damage probability on the plantation area whose distribution is limited in areas with an altitude less than 200 m. The range of TOPEX values also suggests that the plantation areas are located across relatively protected to overly exposed areas. The probable impact of elevation and wind exposure on wind damage might be common knowledge in areas where wind damage is adequately studied but in countries like the Philippines this is relatively new. This information is relevant as most forests especially plantations in the country are situated in hilly and mountainous areas with rugged terrains. Site exposure is not normally considered in terms of identifying suitable plantation areas and more so in identifying areas with high risk of damage due to strong winds.

4.4.3 Critical stand height levels for plantation areas

Wind damage probability models are important in estimating risks of damage but at the ground level where actual plantation and management works are being implemented, a risk map would be more useful. A wind damage risk map derived from the parameters of the best fit probability model could help managers detect areas with high or low susceptibility of damage. The topographical characteristics of the vulnerable sites may be hard to control, but the models and maps could guide managers in making appropriate decisions on harvesting and silvicultural treatments to reduce the level of damage. Valinger and Fridman (1999) suggested that it may be best to shorten rotations on high-risk sites and impose longer rotations on low-risk sites. With such recommendations, the question of what is the appropriate "short" and "long" rotation period to reduce damage remains.

The study developed the damage risk map to further guide the forest manager in determining the critical stand heights at which the sites will be rendered susceptible to damage. This stand height value could be used along with site index information to determine the rotation age at which the critical level of height will be reached. This gives an indirect estimate of the risk-sensitive rotation period at which each site might be managed to reduce losses from wind damage brought about by a strong storm or typhoon.

4.4.4 Importance of DEM models

In the study, elevation and TOPEX variables were derived from DEM. Ni Dhubhain *et al.*, (2001) pointed out that one of the hindrances to using wind throw models in the past has been the cost and difficulty associated with collating stand and site factors and costly field surveys. The use of DEM can help solve this problem. However, the use of DEM also has its limitations, and it must still be combined with detailed stand inventories and record-keeping to come up with effective wind damage models.

4.4.5 Model and study limitations

It is important to note that the damage probability model used in the study has a number of limitations. Wind damage to plantations in the Philippines is a completely unexplored aspect resulting to limited data available for modeling. The results of the study is not comprehensive and some stand attributes (species composition and proportion, density, diameter, basal area, soil properties, silvicultural treatment) that were not tested may also be influential in determining wind damage probability. Also, damage probability was estimated from the impact of one typhoon event and contributing factors may vary from one event to another (Valinger and Fridman, 2011; Albrecht *et al*., 2012 ; Kamimura *et al*., 2013). There is a considerable difference between the damages incurred by storms and typhoons even if they occur on the same area. Future challenges include the possible inclusion of damage analysis from previous typhoons and future occurrences along with detailed stand and site descriptors. Risk analysis is an important consideration on long-term investments like plantation development and even with these limitations the results of the study has provided baseline information and introduced the potential of using the method to help forest managers assess wind damage risk to plantations.

4.6 Conclusion

The study developed an adequately fitting model to estimate wind damage probability on a plantation of short-rotation softwood species. The best-fit model includes average stand height, elevation, and topographic exposure as influential stand-level variables in predicting the probability of damage from strong winds caused by storms. The parameters of the selected predictor model were used to develop a damage risk map which is a valuable tool at ground-level planning and management. The risk maps were projected to show varying levels of site susceptibility given an increase in average stand height. The risk map guides the identification of high and low-risk areas and provides information on the critical stand height at which sites will be rendered susceptible to damage. The critical stand height information along with site productivity information could then be used as a basis for determining the risk-sensitive rotation age at which certain species can be grown.

The factors used in the study are easily measured topographic attributes that were derived from DEM. This however should be supplemented with detailed site and stand inventories to further improve model accuracy. The study used limited data whose accuracy is not always certain so it is therefore recommended that future studies include other factors (stand, site as well as wind characteristics) and regular updating of damage inventory should be done.

In the Philippines, it is widely recognized that risk management should be considered especially for long-term investments like tree plantations. However, the absence of damage assessment on forests and plantations indirectly suggests that these risks are not seriously considered in planning. With the onset of climate change and as areas experience more intense damage from weather disturbances, it is high time that risk assessment and analysis be taken seriously. The results of the study provide baseline information and contribute to that initial step of integrating risks to plantation development and management.

Chapter 5

Optimal species-site assignment and harvest schedules integrating site productivity and risk considerations

5.1 Introduction

Forest management is a complex process which requires decisions for various goals such as timber production, biodiversity, carbon sequestration, aesthetics and many others (Hotvedt, 1983; Davis *et al.*, 2001). These decisions take into account the forest owner's goals and consider the scarcity and diversity of available resources in the production and maintenance of a myriad of products and services from a forest over a relatively long period of time (Hotvedt, 1983). The complex nature of forest management problems arises from conflicting and often competing goals, scarce resources and the long time frame involved in forestry-related investments. Fonseca *et al*. (2012) added that forest management and planning have evolved from relatively simple stand rotation decision-making and has now embraced industrial approaches for timber production while meeting other conflicting demands such as for non-timber resources. These considerations put forest management and planning in a more complex level which involves economic, social and environmental issues prompting the use of multi-criteria decision approaches.

Timber management, which is an integral part of forest management, follows the same complexity in resolving two of its traditional tasks, which are establishing harvest schedules and developing a regulated forest (Hotvedt, 1983). Harvest scheduling which is at the core of timber management involves the temporal and spatial scheduling of harvest under a regulation consideration and considers requirements on growing stock and harvest volumes, growth rates, and cash flow (Hotvedt, 1983; Walters, 1997; Duangsathaporn and Prasomsin, 2005; Watanabe and Tatsuhara, 2013).

St. John and Toth (2013) stated that due to the combinatorial complexity of timber harvest scheduling problems which requires large areas and long time horizons, they are typically cast as optimization problems and solved with operations research techniques. The field of operations research (OR) comprises a rich collection of analytic techniques that have been developed over the last 50 years to solve complex problems arising in all aspects of human activity including forest management and harvest scheduling problems (Jensen and Bard, 2003). OR techniques such as mathematical programming (Pukkala and Pohjonen, 1990; Diaz-Balteiro *et al*., 2009; Watanabe and Tatsuhara, 2013) and meta-heuristic approaches (Abdullah *et al*., 2014) are often used in optimizing harvest schedules . Abdullah *et al.,* (2014) stated that mathematical programming techniques such as linear programming (LP) are being used to generate optimal solutions in large forest areas without spatial constraints while integer programming (IP) and mixed IP (MIP) have been proposed for smaller forest areas with spatial constraints. On the other hand, meta-heuristic approaches have been used for larger-sized problems which incorporate several spatial constraints or in cases when it is not possible to find a solution from mathematical programming (Fonseca *et al.,* 2012; Abdullah *et al*., 2014). These approaches include Monte Carlo programming (MCP), Tabu Search (TS), simulated annealing (SA), threshold acceptance (TA) and genetic algorithm (GA).

Mathematical programming methods in the form of LP and its variants already have a long history in terms of its use in harvest-scheduling. Hotvedt (1983) noted that forest management planning techniques that were developed in the past decades to solve harvest-scheduling and regulation problems involved linear programming. In the case of mathematical programming techniques, its use dates back from mid-20th century for the proper land allocation in agricultural planning (Sen and Nandi, 2012b) and in forest planning as well (Fonseca *et al.,* 2012; St. John and Toth, 2013). This is further confirmed by other authors who stated that LP is a widely used method in solving long-term forest management problems because it allows versatility and flexibility in modeling the complex constraints of forest management (Pukkala and Pohjonen, 1990; Walters, 1997; Duangsathaporn and Prasomsin, 2005; Ayaji, 2013).

There is a wealth of studies concerning the use of LP and its variants in developing optimal harvest-schedules. A major percentage of literature concerning the use of OR techniques in the harvesting process planning refers to private forest plantations or to natural forests with road building or harvesting machinery location requirements (Fonseca *et al*., 2012) which sometimes involve adjacency constraints, green-up and opening size constraints (Walters, 1997). Haight and Monserud (1990) also stated that in these optimization models, the common objectives of forest managers is between maximizing present of value of cash flow and maximum yield.

LP technique was used in the study of Haight and Monserud (1990) which developed an any-aged management plan for a mixed-conifer stands in Northern Rocky Mountain with the general objective of maximum present value and maximum cubic foot volume. Similarly, Duangsathaporn and Prasomsin (2005) applied LP in designing a management plan for a teak plantation in Thailand. The objective of the study was to maximize NPV of expected yields while being converted from irregular forest to regulated forest plantation. Ayaji (2013) also used LP for managing timber harvests from even-aged Gmelina arborea plantations in Omo forest reserve, southwestern Nigeria. The study's main interest is to maximize wood from the established plantation and generate a constant flow of woods on a sustainable basis. In Spain, Diaz-Balteiro *et al*., (2009) observed several problems attached to current management planning applied on plantations of *Eucalyptus globulus* and proposed a strategic management plan based on LP. The problem formulation took into account the optimum length for one full plantation cycle that maximizes the land expectation value. Aside from solving harvest-scheduling problems, LP was also used by Pukkala and Pohjonen (1990) to analyze the land use alternatives in a fuelwood plantation (*Eucalyptus globulus*) area in the central highlands of Ethiopia. In a similar manner, Sunandar *et al*., (2014) employed LP technique in obtaining the most appropriate land use with the primary objective of minimizing erosion without decreasing water yield inside a watershed.

Due to some limitations of the basic LP technique and the increasing need to maintain other forest values, extensions and some variations of the LP model emerged. These include integer programming (IP) and goal programming (GP). Studies that employed IP in solving harvesting problems include that of Constantino *et al*., (2008) which included adjacency considerations in modeling an optimal harvest schedule plan. Fonseca *et al*., (2012) also used IP in its objective to develop an "easy-to-use" tool to be applied by the forest managers to help schedule the thinning and clear-cutting operations of maritime pine stands situated on common lands in Portugal. St. John and Toth (2013) developed spatially explicit harvest scheduling models with a new IP model, termed as Model IV, to capture maximum harvest opening size restrictions and intermediate treatment decisions. Watanabe and Tatsuhara (2013) used 0-1 IP to formulate a long-term harvest scheduling model for Sugi and Hinoki plantations in Japan, involving two types of rotation and limited by constraints on available size of work force. Abdullah *et al*., (2014) developed an optimization model based on selective cutting to determine harvest areas with the objective of maximizing harvest volume subjected to spatial constraints that protect the non-timber value of a forest, such as biodiversity conservation and wildlife habitat protection.

GP is also prominently used in harvest-scheduling because of its ability to capture the multiple objective nature of timber management and planning. In 1983, Hotvedt applied GP in solving harvest-scheduling problems of a small pulp and paper company to determine the species composition, age and volume of stands thinned and final harvested by period. Bertomeu *et al*., (2009) used GP in developing alternative management plans on coppice stands of Eucalyptus plantations in Galicia, Spain. This study presented an alternative approach to area control that does not impose any specific final age-class distribution of the plantation while fulfilling the objective of a constant timber yield in perpetuity beyond the planning horizon. Similarly, Sen and Nandi (2012a) attempted to formulate a strategic plan for rubber plantations using GP.

As evidenced from above-mentioned studies, LP and its variations are very common forest management tools, particularly for designing optimal harvest-schedules. The common objectives were to maximize net present value of cashflow and flow of harvest for a forest over a planning period under some restrictions. In the case of studies on even-aged forests or plantations in which this study is focused on, most of the published literature deals with optimal management plans for one or two species and only few studies incorporate considerations on productivity. In addition, there are very limited studies that integrate risk considerations of stand damage in designing optimal harvest-schedules.

In the Philippines there had been only a handful of studies employing LP on timber management and they were particularly geared towards optimizing harvests from dipterocarp forests which are under uneven-aged stand management and with a cutting age of 35 years. There were very limited attempts to conduct similar optimization studies on short-rotation multi-species plantation which are usually the case of industrial tree plantations in the country. However, these studies remained in paper and were not implemented as forest management on the ground still relied on previous “systematic” planning of harvest schedules. The same could be said for shorter-rotation plantations of fast-growing species. There is no record of any mathematical programming derived harvest scheduling program that have been applied to forest plantations in the Philippines.

The current management plan for the study area indicates that the harvest-schedules of plantation areas are designed using the area control method. It is stated that plantation stands shall be clear-cut as soon as they reach the rotation age. It does not take into account the site productivity with respect to target species and neither does the plan indicate if the current harvest-schedule maximizes profit or yield over a period of time. The assignment of species to a site is rather arbitrary and somewhat trial-and-error in nature. In the same way, potential impacts of damage to plantation growth and profitability are not considered in planning. However, it is indicated that if damage to the plantations happens, management plans can be revised to consider changes accruing from these events. This is a clear indication that potential risks are anticipated, but actions are delayed until the impacts of these risks are actually realized.

From these observations, it can be stated that though harvest-scheduling currently practiced in the study area follow an empirical manner, there are also times when arbitrary decisions are made on assigning species to a site and harvesting without in-depth understanding of its overall impact on future harvests, plantation growth and profitability. These issues highly warrant changes and improvements to plantation management and planning in the country. It is for these reasons that this study was conducted. The study introduces a method of improving plantation management in the Philippines by developing optimal models for species-site assignment, which at the same time provide a stable flow of harvests and income through time. These models incorporate knowledge on site productivity and consider critical rotation ages as determined from the site’s level of risk to wind damage caused by strong typhoons. Specifically, the study aims to use integer programming (IP) in order to 1) develop optimal species-site assignment models considering site productivity and multiple target species, 2) develop optimal harvesting schedules by incorporating risks of stand damage from occurrence of storms and typhoons, and 3) identify the trade-offs between two different management objectives of maximizing volume production and net present value.

5.2. Methodology

The study used IP in developing optimization models for species-site assignment and harvest-schedules. The optimization was done by using considerations on site productivity (Chapter 3) and site risk to wind damage (Chapter 4).

5.2.1. Attributes of target species and management units

First, the site productivity of the management units (compartments) for each species was derived from the results of Chapter 3. Specifically, the site productivity estimates based on common variable model were used in the optimization. In Chapter 3, raster maps were developed from resulting site productivity models, and these were used to generate the site productivity information of each compartment used in the optimization. Other spatial data such as initial age, dominant species and the areas of each compartment were all derived from plantation documents and inventory records and verified during field works.

Secondly, the study aimed to develop optimal harvest-schedules while considering the risk of wind damage to plantations. Recently, the study area has been experiencing substantial damage from storms and typhoon. The current management plan however does not include any provision for managing these risks. From the previous chapter, the risk of wind damage to the plantation area was modeled, and risk maps were developed. The information on critical stand height level at which each compartment is at high risk of being damaged was also derived. Using the site index information of the site and height equations for each species from Table 3.2, the rotation age at which the critical height levels, or the risk-sensitive rotation age, will be reached was determined. The resulting risk-sensitive rotation ages used for each compartment and for each species are presented in Table 5.1. At current management scenario, *P falcataria*, *A. mangium* and *G. arborea* are managed at a rotation age of 12 years while *E. peltatum* is managed at a longer rotation age of 20 years. In considering risks of wind damage to plantation and depending on the site productivity, risk models suggest a 4-year rotation for *P. falcataria* and *E. peltatum* on high-risk sites. On the other hand, 5 and 8 years were the suggested rotation ages for *G. arborea* and *A. mangium*, respectively. For medium-risk sites, *P. falcataria* could be managed at rotation ages 7, 8 and 9. In the case of *E, peltatum*, shorter rotation periods with a length of 5, 6 and 7 years could be used. On the same site, *A.mangium* and *G. arborea* have longer risk-sensitive rotation ages of 9, 10 and 12. For low-risk sites, *A. mangium, G. arborea*, and *P. falcataria* could be grown at a rotation age of 12, 14 and 15 years, respectively. On the other hand, *E. peltatum* could be grown on low-risk sites at shorter rotations of 8 and 9 years.

Table 5.1 Risk-sensitive rotation ages used for each species considering level of site risk

Level of site risk	Species *P. falcataria*	*E. peltatum*	*A. mangium*	*G. arborea*
High	4	4	8	5
Medium	7,8,9	5,6,7	9,10,12	9,10,12
Low	14	8,9	12	15

Using the information on site productivity, the harvestable volume at rotation age (from risk models) of each compartment was computed using published yield equations (Table 5.2).

Table 5.2 Yield equations used for computing yield for each species in each compartment

Species	Equation	Author
P. falcataria	Log Y =1.5366 + 0.2009 Log A + 1.4645 Log SI + 0.6325 Log (A*SI)	(Revilla, 1974)
E. peltatum	Log (Y+1) = -11.1579 + 9.4881 Log SI – 4.2273 Log A* Log SI – 1.0136 (Log SI)^2 + 7.6545 Log A	(Ramos, 1977)
A. mangium	Y = 8.122 A + 65.284 Log SI + 1.146 (Spacing) – 118.493	(Palma *et al.*, 2006)
G. arborea	Log (Y+1) = -0.0292 – 5.3479/A + 0.0889 SI/A + 1.7597 Log SI	(Lingan, 1979)

Y= yield (m^3/ha), A= age in years, SI=site index (m), Spacing used for all species is 4 x 4 m which translate to about 625 trees/ha

5.2.2 Cost and income assumptions

In this study, timber production is the only forest function considered in the optimization. Pukkala et al., (2011) noted that forestry creates significant externalities such as carbon sequestration, non-wood products, recreation possibilities, and biodiversity conservation and though forest owners do not directly benefit from them they should still be considered in management planning. However, the plantation under study is exclusively managed for timber production as raw material for veneer production, pulp and paper and other wood products such as wood pallets and matchsticks. Because of this, potential outputs like carbon sequestration, biodiversity conservation, aesthetics and others are not considered in the study.

The silvicultural system prescribed for all compartments is clear-cutting which is the only silvicultural method applied by the company to the plantation area. It is also assumed that whenever management units are cut, it was immediately replanted in the same year. Intermediate treatments included are those described in the management plan. The company does not practice any thinning methods throughout the rotation period, so costs and potential income from this activity is not included in the study. As for timber prices and management expenses, it was assumed that they were constant all throughout the planning horizon. It was also assumed that the goal of management was either to maximize net present value of cash flow or to maximize total harvestable volume over the entire planning horizon.

The income and cost assumptions were all provided by the management and field staff of CSDC and verified from plantation documents and management plans. With regards to cashflow, the revenues from the final harvest were the only income considered. The timber produced from the plantations are treated as a log mix regardless of species and are channeled directly to the company's partner wood processing plant (WPP). The timber price of Php 4,500 (Philippine pesos, 1 Php = 0.02 US$) imposed by the WPP per cubic meter of log mix was used in the optimization. However, it must be noted that in different parts of the country, the target species command different prices. These species may command higher price in one region but may be valued at a lower price in other regions of the country. Other management costs included planting costs, harvesting costs, and overhead costs. Planting costs cover plantation establishment, nursery cost, and plantation care and maintenance. The total cost of plantation establishment is Php 5,500 per hectare and covers activities such as under brushing, partial cutting, staking and planting. For each compartment, a fixed per-hectare planting cost is assumed after every cutting at rotation age. Nursery cost is Php 2,250 per hectare under a 4 x 4 spacing policy and considering a 20% allowance for mortality of seedlings. Plantation care and maintenance costs extend from the initial year of plantation establishment up to the third year. For the first year, the cost of plantation care and maintenance is Php 4812.50/ha and includes two rounds of fertilizer application, blank filling, and four passes of weeding application. In the second year, cost is reduced to Php 988.00/ha to cover the last round of weeding activity. Finally, in the third year, a cost of Php 468.75/ha is considered for the pruning of 3-year old stands. On top of the harvesting cost of Php 2,000 per cubic meter, a forest charge of Php 95 x 40% of harvested volume is also included in the costs. Lastly, since the plantation under study is managed on an industrial scale, overhead costs in the form of administration and protection activities are a major part of cost considerations. The overhead cost is about Php 1860/ha/yr.

All costs and revenues were computed using a 15% discount rate which is the prevailing discount rate used in evaluating forest and plantation investments in the Philippines (PCARRD, 2007). A planning horizon of 50 years, subdivided into 5-year intervals or 10 working periods was used in the computation of optimization models. The 5-year interval working period is in accordance with the IFMA requirement of strategic planning for every five (5) years.

5.2.3 Harvesting Decision

In order to facilitate the optimization process, harvest decision matrices for each compartment for each working period was simulated. The harvest decision for each working period depends on initial species composition, initial age of stands in the compartment, species to be assigned and rotation period based on risk level. The first two working periods are designated as the conversion period which means that conversion of compartments from current species composition to optimal species-site assignment should be completed in the first ten (10) years of the planning horizon. There are two criteria set for harvesting compartments in the conversion period. The first criterion is that all compartments whose age at the end of the first working period is equal to or higher than the suggested risk-sensitive rotation age will be harvested and converted. The second criteria is that compartments which are not harvested in the first working period because they have not reached the risk-sensitive rotation age but whose species composition does not match that of assumed optimal condition will be harvested and converted in the second working period. For example, if the optimal condition calls for a compartment to be assigned to *P. falcataria* but its current species composition is of a different species, then it will be harvested in the conversion period. The harvesting decision for the next working periods is based on the risk-sensitive rotation ages. It is assumed that after the conversion period, compartments will be immediately replanted with the right species and will follow the rotation age set for that species and level of site risk. All compartments are assumed to be replanted in the same working period after they are harvested.

5.2.4 Problem Formulation

The problem was formulated in such a way that it answers the question of what is the optimal species-site assignment that maximizes the management objective and at the same time provides a harvest schedule that will ensure stable flow of harvests and income in each working period and for the entire planning horizon.

Integer programming using binary variables 0 and 1 was used to solve the problem. It is formulated as such because of the assumption that compartments are not to be broken up during harvesting. Using the site productivity information of each compartment, the yield at rotation ages and net revenue for each compartment for all species were projected for 10 working periods. The problem was formulated as follows,

$$\text{Max Z} = \sum_{i=1}^{I}\sum_{j=1}^{J} R_{i,j}X_{i,j} \qquad (Eq'n.1)$$

$$\text{Max Z} = \sum_{i=1}^{I}\sum_{j=1}^{J} V_{i,j}X_{i,j} \qquad (Eq'n.2)$$

Subject to

$$X_{i,j} \in \{0,1\} \qquad (Eq'n.3)$$

$$\sum_{j=1}^{J} X_{i,j} = 1 \quad \forall i \qquad (Eq'n.4)$$

$$\sum_{i=1}^{I} X_{i,j} \geq 1 \quad \forall j \qquad (Eq'n.5)$$

$$(1-\propto)\sum_{i=1}^{I}\sum_{j=1}^{J} v_{i,j,t-1}X_{i,j} \leq \sum_{i=1}^{I}\sum_{j=1}^{J} v_{i,j,t}X_{i,j} \leq (1+\beta)\sum_{i=1}^{I}\sum_{j=1}^{J} v_{i,j,t-1}X_{i,j} \ ,$$

$$t = 2,3,\dots,T \qquad (Eq'n.\ 6)$$

where, Z is the value of the objective function; I is the number of compartments (27); J is the number of species (4); T is the number of working periods (10); $R_{i,j}$ is the total net present value from all working periods when compartment i is assigned to species j; $V_{i,j}$ is the total harvestable volume from all working periods throughout the planning horizon when compartment i is assigned to species j; $v_{i,j,t}$ is the volume of harvest when compartment i is assigned to species j at time period t; $\propto and\ \beta$ are the allowable percentage of increase and decrease in volume of harvest from the previous working period;; and $X_{i,j}$ is 1 when compartment i is assigned to species j and 0, if otherwise.

5.2.5 Formulation of objective functions

Species-site assignment and harvest schedules were optimized under two general objectives (1) maximize total harvestable volume (THV) and (2) maximize net present value (NPV). Walters (1997) stated that in terms of industrial forest management where harvest scheduling is much more intensified, the objectives of optimization are dominated by profit maximization and cost reduction. On the other hand, Hotvedt (1983) emphasized that maximizing total volume over a planning period is a usual objective in harvest-scheduling problems involving LP because of the biological nature of forest management. In the case of the study, the maximization of NPV is a foremost objective, but the objective on maximizing total harvestable volume is also added to identify tradeoffs if any one of the two objectives is pursued. In addition, this is to give the managers an alternative option in the event that they decide to switch objectives.

For the objective of maximizing THV, $V_{i,j}$ represents the total harvestable volume from all working periods for the length of the planning horizon if compartment i is assigned to species j and it is computed as follows,

$$V_{i,j} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} v_{i,j,t} \quad (Eq'n.7)$$

In terms of maximizing net present value, $R_{i,j}$ is computed as,

$$R_{i,j} = \frac{1}{(1+a)^{tl}}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} r_{i,j,t} \quad (Eq'n.8)$$

$$r_{i,j,t} = Pv_{i,j,t} - (C_h + C_p + C_o) \quad (Eq'n.9)$$

where, $r_{i,j,t}$ is the undiscounted net revenue when compartment i is assigned to species j at working period t; a is the interest rate (0.15); l is the length of each working period (5 years); P is timber price (Php 4,500/m^3); C_h is harvesting cost; C_p is planting cost; C_o is the overhead cost. The value of net revenue, $r_{i,j,t}$ is derived from the difference of total income from harvests and total costs from harvesting, planting and overhead (administration and forest protection) costs.

5.2.6 Formulation of model constraints

Equations 3-6 represent the constraints used in the optimization. The values of $X_{i,j}$ are set to binary (0,1) (Equation 3) wherein a value of 1 indicates that a compartment is assigned to a species and a 0 value, if otherwise. For the optimization process, compartment and volume restrictions were imposed. Equation 4 is the constraint that limits the assignment of a compartment to only one species. Equation 5 sets the minimum number of compartments to be assigned to each species where each species should be assigned to at least 1 compartment. Lastly, to ensure a stable supply of harvests and consequently income, a restriction on total harvestable volume (Equation 6) for each working period is added. In this case, the minimum and maximum fluctuations of harvest of each working period from the last working period are set to 20%. Diaz-Balteiro *et al.* (2009) also used the same allowable deviation for short rotation Eucalyptus plantations.

5.2.7 Problem solution

As a result of problem formulation there were a total of 108 variables (27 compartments x 4 species to be assigned) and 49 constraints. The binary form of IP was used to ensure that compartments will not be divided during harvesting and that only one species will be prioritized per compartment. In addition, the management objectives to maximize NPV and THV were used as scenarios in the optimization models. The problem was solved with the use of Solver tool pack in Excel. The results of the optimization models were then imported to GIS to provide a visual lay-out of species-site assignment.

5.3 Results

5.3.1 Optimal species-site assignment models

The IP model produced optimal solutions to the species-site assignment problem using site productivity information and rotation age considering risks under stable harvest restrictions. Optimal species-site assignment model were derived for two management scenarios, 1) maximize THV and 2) maximize NPV. Table 5.3 shows the results of the optimization process under two scenarios.

The species-site assignment that will maximize the amount of total harvestable volume during the planning horizon is achieved under scenario 1. Scenario 1 yields a total of 2,580,180 m^3 of timber by assigning majority of the compartments (17) to *E. peltatum*, 8 compartments to *P. falcataria* and 1 compartment each to *A. mangium* and *G. arborea*. Under this scenario, *E. peltatum* is prioritized in about 65% (2,263 ha) of the plantation area, devoting only 29% (1020 ha) to *P. falcataria* and only about 3% each for the two remaining species.

On the other hand, NPV is maximized by the species-site assignment model resulting from scenario 2. At this scenario, NPV from all working periods is

579,254,495 Php. This value is achieved by assigning 15 compartments to *E. peltatum*, 10 compartments to *P. falcataria*, and 1 compartment each to *A. mangium* and *G. arborea*. This translates to assigning about 56% of the plantation area (1,964 ha) to *E. peltatum* and 37% to *P. falcataria* (1,306 ha).

Comparison between the THV and NPV values of two scenarios showed only a small difference between the two. The THV value of scenario 2 is only 1% lower than that of scenario 1 with a difference of 33,919 m^3. Similarly, the NPV value of scenario is down by only 1% compared to scenario 2. The difference between the NPV of two scenarios is about 3,202,665 Php.

Comparison between species revealed that under scenario 1, about 70% of the total volume production comes from *E. peltatum*, followed by *P. falcataria, G. arborea,* and *A. mangium.* Consequently, a major percentage of NPV comes from *E. peltatum* (68%) also, followed by *P. falcataria, G. arborea,* and *A. mangium.* In the case of scenario 2, volume contribution from *E. peltatum* is decreased to 63%, followed by *P. falcataria, G. arborea,* and *A. mangium.* NPV contribution at this scenario is at the highest with *E.peltatum* (54%), followed closely behind by *P. falcataria* (42%) and then by *G. arborea* and *A. mangium.*

The resulting optimal species-site models under both scenarios completed the conversion of compartments in two working periods, specifically in the first 6 years of the planning period. The two scenarios also selected the same set of rotation periods depending on the site's level of risk (Table 5.4). For *P. falcataria*, the rotation ages used were 4, 8, 9 indicating that at an optimal condition, all compartments will be managed at ages shorter than the currently practiced rotation. A similar case is observed for *E. peltatum* and *G. arborea* in which shorter rotation ages than usually practiced are also imposed. For *A. mangium*, the same rotation age of 12 years as usually practiced is selected.

Comparing species assignment and site risk levels showed that in both scenarios, optimal solutions show a great tendency to assign short-rotation (4 years) of *P. falcataria* on high-risk sites and medium rotations (8-9 years) of *E. peltatum* on low-risk sites. Under scenario 1, majority of the sites assigned to *E. peltatum* (88%) are those of the medium-risk sites, the same goes for *P. falcataria, A. mangium* and *G. arborea*. In scenario 2, the dominant site assignment for *P. falcataria, A. mangium* and

Table 5.3 Results of optimal species-site assignment models for scenarios 1 and 2

Scenario	Species	THV (m^3)	NPV (Php)	No. of Compartments Assigned	Total Area Assigned (ha)	TV per species (m^3)	NPV per species (Php)
1	*P. falcataria*	2,580,180	576,051,830	8	1020	660,301	160,775,005
	E. peltatum			17	2263	1,840,732	394,105,631
	A. mangium			1	104	28,150	4,642,419
	G. arborea			1	111	50,997	16,528,775
2	*P. falcataria*	2,546,261	579,254,495	10	1306	857,094	243,111,268
	E. peltatum			15	1964	1,613,308	313,106,872
	A. mangium			1	117	24,863	6,507,580
	G. arborea			1	111	50,997	16,528,775

Table 5.4 Number of compartments and rotation ages assigned at optimal conditions per level of site risk for each species

Scenario	Species	Level of site risk				Assigned Rotation Age (years)
		Low	Medium	High	Total	
1	*P. falcataria*	0	5	3	8	4,8,9
	E. peltatum	2	15	0	17	5,6,7,8,9
	A.mangium	0	1	0	1	12
	G. arborea	0	1	0	1	10
2	*P. falcataria*	0	7	3	10	4,8,9
	E. peltatum	2	13	0	15	5,6,7,8,9
	A.mangium	0	1	0	1	12
	G. arborea	0	1	0	1	10

G. arborea are still on medium-risk sites. As for *E. peltatum*, 87% of the site assignment is of the medium-risk level sites. Exporting the results of species-site assignment models into GIS facilitated the development of a map lay-out of species-site assignment (Figure 5.1). The map provides a visual guide to which particular compartments are assigned to each species under different scenarios. Mapping the layout of species-site assignment per scenario shows that the species-site assignment generally varies with different management objectives. Only about 78% of the compartments (21) retain the same species assignment under different scenarios of management objectives while the rest change species assignment depending on the objective being maximized. The map also facilitates comparison between optimal species-site assignment and current species composition. The comparison showed that for both scenarios, about 59% of the compartments (16) are not currently planted with their optimal species assignment.

5.3.2 Flow of harvest volumes

A steady flow of harvests across the length of the planning horizon is a prime consideration in developing timber harvesting schedules as the flow of income from each working period depends on the amount of harvest. In the optimization scenarios, a 20% fluctuation in harvested volume between working periods was allowed. The resulting flow of harvests from one working period to another for the two scenarios is presented in Figure 5.2. As mentioned above, scenario 1 yields higher THV than scenario 2 but only by a small amount. The mean volume of harvest for scenario 1 is 258,018 m^3, wherein the highest volume is harvested at the last working period (279,700 m^3) while the lowest volume of harvest occurs at the 4^{th} working period (233,168 m^3). On the other hand, the mean volume of harvest from scenario 2 is 254,626 m^3 with the highest harvested volume occurring at the first working period (278,761 m^3) and the lowest volume is harvested at the 9^{th} working period (227,261 m^3). Although, THV is higher in scenario 1, the mean fluctuation in volume harvested between working periods is also higher than in scenario 2. In scenario 1, the mean difference between harvests at each period is about 26,928 m^3. On the other hand, in scenario 2, the mean deviation in harvests is only 18,959 m^3 indicating a more stable supply of harvest from one working period to another than in scenario 1.

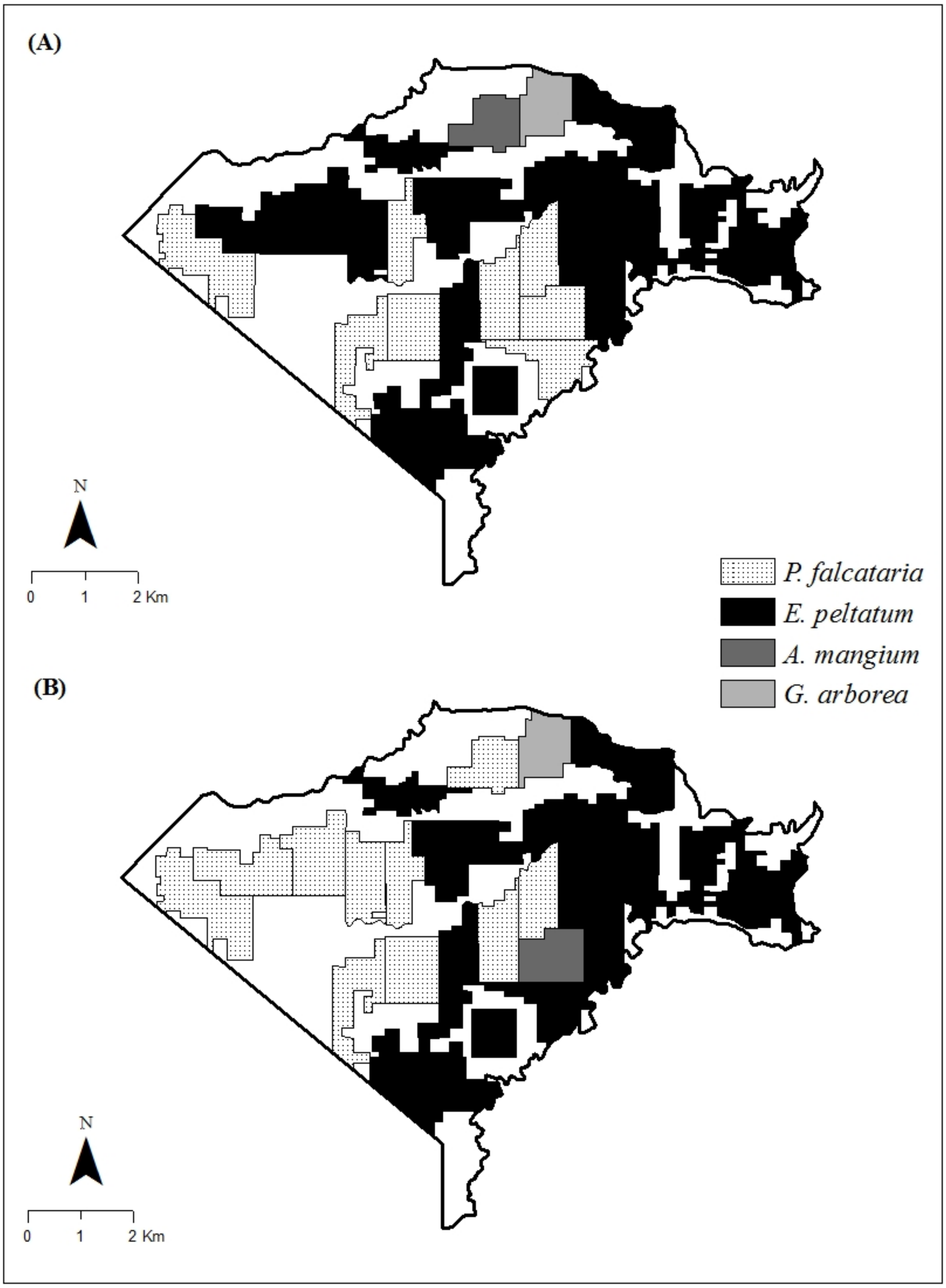

Figure 5.1 Species-site assignment map for different species under (A) Scenario 1 (maximize THV) and (B) Scenario 2 (maximize NPV)

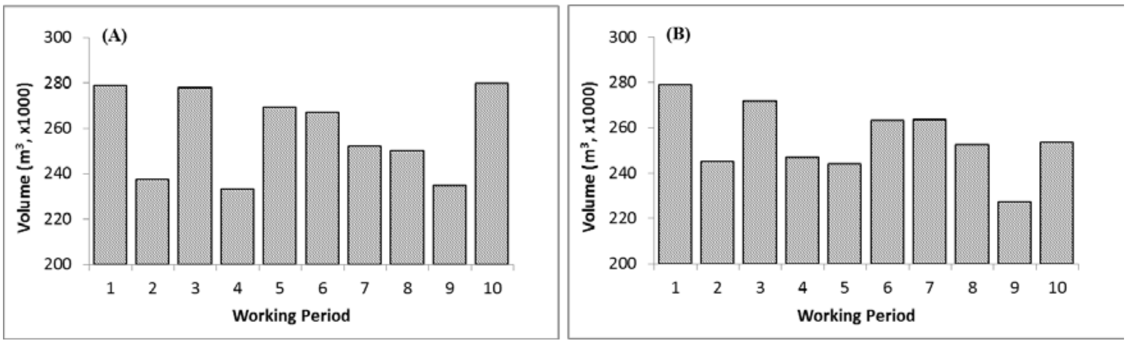

Figure 5.2 Flow of total harvestable volume from each working period under scenario 1 (A) and scenario 2 (B)

5.3.3 Flow of harvest areas

The total harvest areas for each working period under the two scenarios are presented in Figure 5.3. The total harvested area for the whole planning period is higher in scenario 2 than in scenario 1, which has a total of 23,974 ha. Total area harvested for scenario 1 is lower by 4% at 23,091 ha. For scenario 1, the peak of harvest areas is in the 5th working period while the lowest is in the 9th working period. Under scenario 2, the highest number of harvest areas occurs also at the 5th working period while the lowest occurs at the 3rd working period. The difference between harvest areas in scenario 1 ranged from 16-411 ha with a mean difference of 177 ha. On the contrary, the difference between harvest areas of scenario 2 ranges from 8-374 ha with a mean difference of 159 ha. The seemingly big range of differences in areas harvested per working period for both scenarios stems from the restriction that each compartment could not be broken up for harvesting.

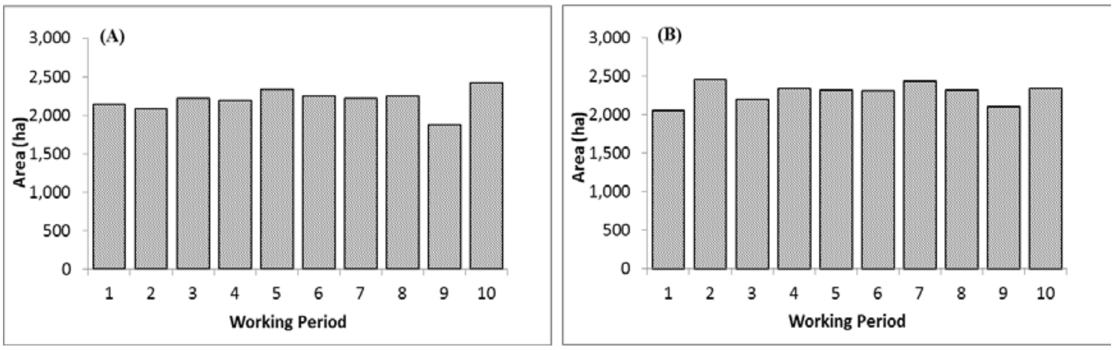

Figure 5.3 Harvest areas for each working period under scenario 1 (A) and scenario 2 (B)

5.3.4 Flow of net revenue and NPV

Another important consideration in scheduling timber harvests is the flow of income and long term financial benefits in the form of NPV. The flows of undiscounted net revenue and NPV from each working period for both scenarios are projected in Figures 5.4 and 5.5, respectively.

Total undiscounted revenue of scenario 1 is computed at Php 5.7 Billion, which is slightly higher than the total undiscounted revenue from scenario 2, which is Php 5.6 Billion. The highest net revenue for scenario 1 is incurred at the last working period and has a value of Php 617.4 Million while the lowest net revenue is at the 4th working period with a value of Php 509.1 Million. In the case of scenario 2, the highest net revenue is at the 9th working period (Php 617.0 Million) and the lowest value is incurred 9th working period (Php 495.2 Million). These trends observed for both scenarios coincide with the rise and fall of harvest volumes in each working period. Under scenario 1, undiscounted net revenue fluctuates at an average of Php 63.4 Million between working periods. In scenario 2, a lower mean fluctuation of Php 45.2 Million between working periods is observed. These trends on fluctuations on net revenue suggest that a more stable flow of income is achieved under scenario 2.

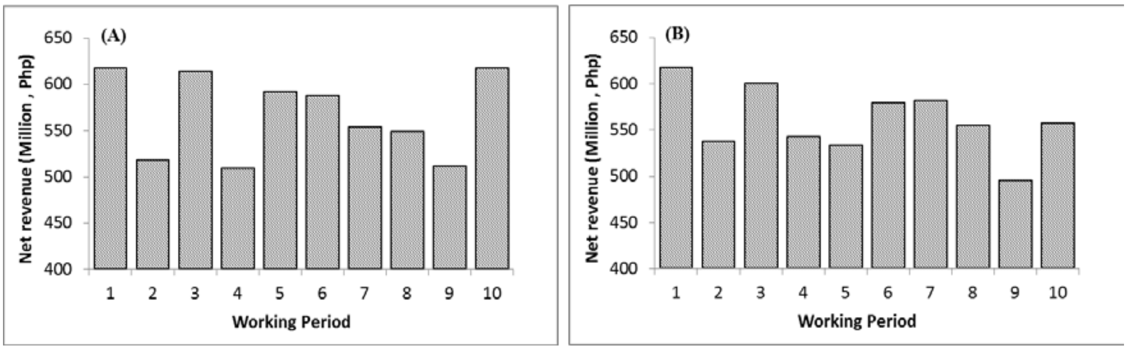

Figure 5.4 Flow of undiscounted net revenue from each working period for scenario 1 (A) and scenario 2 (B).

Aside from the undiscounted net revenue, NPV is another important consideration in managing timber harvest schedules. NPV represents the long-term financial benefits from timber harvests and considers the time value of money. Total undiscounted revenue might be higher in scenario 1 than in scenario 2, but computing the NPV of these net revenues revealed that NPV is higher in scenario 2 than in scenario 1. The mean NPV of scenario 2 which is Php 57.9 Million is slightly higher than the mean NPV of scenario 1 which is Php 57.6 Million. The long term financial benefit is higher in scenario 2 due to the fact that high net revenues occur at the early working periods as opposed to scenario 1 where there are higher net revenues but occurring at later periods. For both scenarios, reductions in NPV appear similar. In scenario 1, NPV is reduced by 41-60% and in scenario 2, reductions range from 43-56%. In Scenario 2, the higher value of NPV is brought about by reducing compartments assigned to relatively longer rotation of *E. peltatum* and assigning them to shorter rotations of fast-growing *P. falcataria*. This confirms that higher NPV could be achieved if plantations are managed under a shorter rotation period.

5.3.5 Age class structures

The optimal solutions given by scenarios 1 and 2 suggest different rotation periods at which each species and compartment will be managed. Rotation periods used range from 4-12 years indicating that harvesting at these rotation periods may result to different age class structures at the end of each working period. Figures 5.6 and 5.7 show the transition of age class structure after each working period under the two management scenarios where each age class represents a 2-year width.

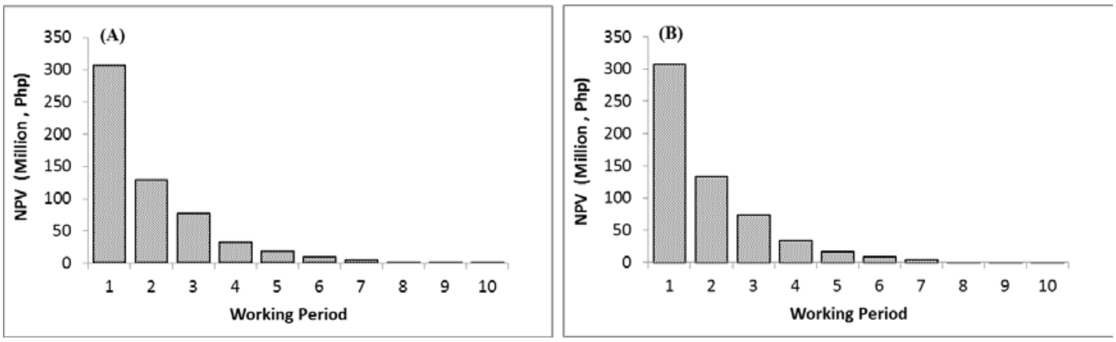

Figure 5.5 NPV of each working period for scenario 1 (a) and scenario 2 (b)

The age class structure at initial condition (Figure 2.3, Chapter 2) shows an abundance of young plantations with areas dominating age classes 2 and 3. These are also few mature stands at age classes 6 and 7 but stands at age classes 4 and 5 are evidently missing. The optimal solution under both scenarios resulted to a more distributed age class structure than the initial condition, where stands are distributed from age classes 1 to 6. Both scenarios appear to have a similar age structure after the first working period indicating that they followed the same conversion process. This is also confirmed by the similar values of harvested volume, net revenue and NPV for both scenarios in working period 1. However, the two scenarios resulted to a different age class structure after that because they imposed varying rotation ages for each species in each compartment. After working period 1, the increase in the areas of young stands (age classes 1-3) is observed to generally happen every 3 working periods under both scenarios. Also in both scenarios, an increase in areas of mature stands (age classes 4-6) is observed to happen in two to three working periods. In terms of ending age class structures, there is a decrease of age classes from 7 (13-14 years) in initial condition to 5 or 6 age classes (10-12 years) in both scenarios. At the end of the planning period, scenario 1 has more areas in age classes 3, 2 and 1 and less areas in age classes 4 and 5. Under scenario 2, the dominant age class is age class 3 followed by age classes 1 and 2. Scenario 2 has relatively more areas allocated in the older age classes (age class 4-6) than scenario 1 indicating that a more mature age class structure is achieved under scenario 2.

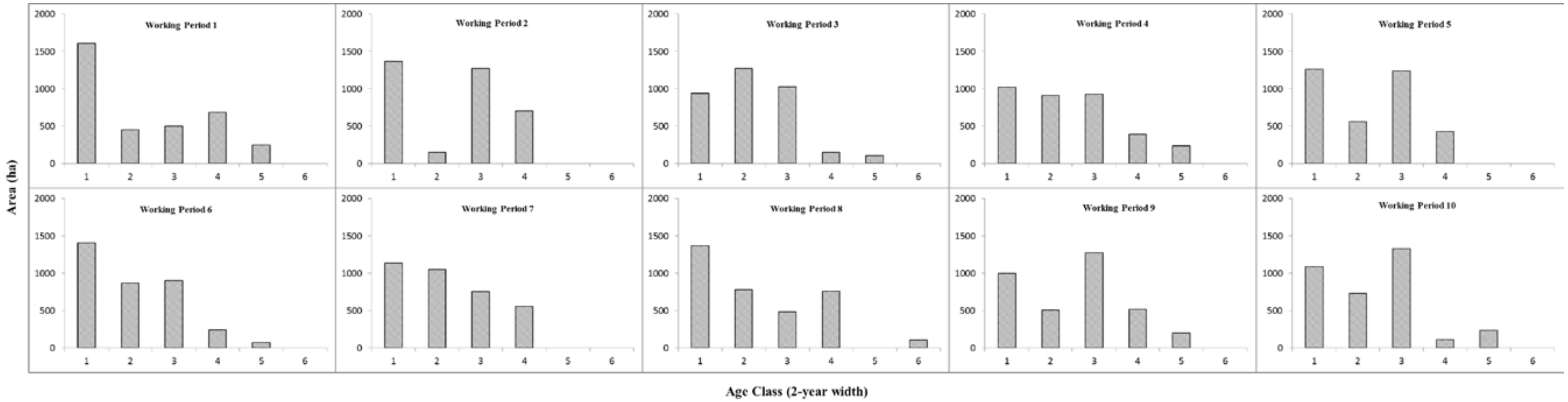

Figure 5.6 Transition of age class structure after each working period under scenario 1

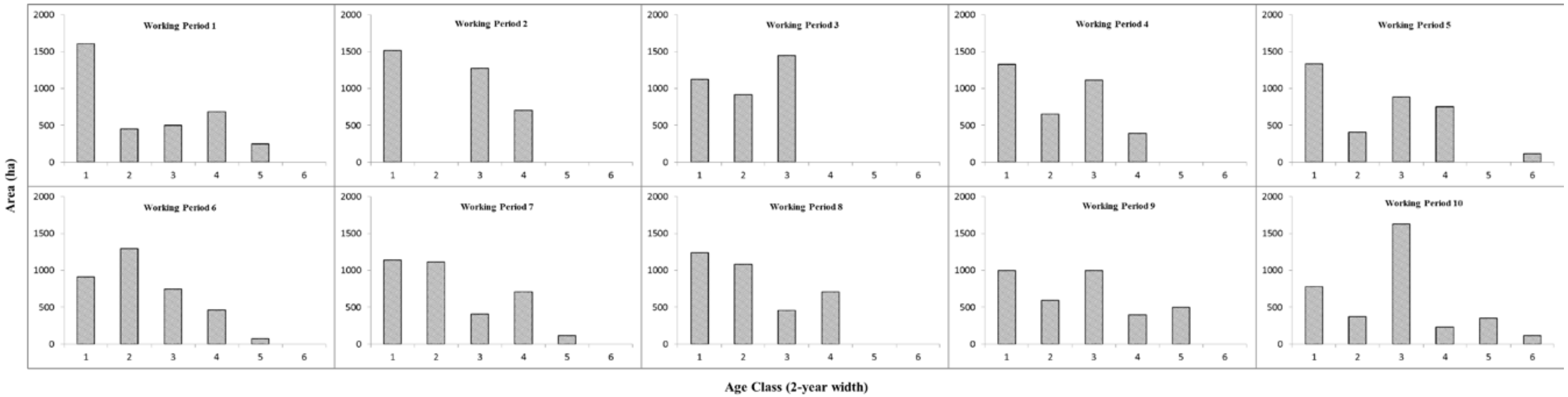

Figure 5.7 Transition of age class structure after each working period under scenario 2

In terms of individual species, the age class structures at the end of the planning period differ under both scenarios in terms of distribution (Figures 5.8 and 5.9). For *P. falcataria*, ending age class structure under scenario is concentrated in age classes 1-3, whereas in scenario 2 the stands are distributed in age classes 1, 3 and 5. In the case of *E. peltatum*, most of the areas assigned to this species are in age classes 1-3 with few areas in age class 5. Meanwhile, its ending age class distribution under scenario 2 is distributed from age classes 1-5 with most of the areas devoted to younger age classes 1-3. The ending age class for *A. mangium* is age class 5 and 6 for scenario 1 and scenario 2, respectively. Finally, the age class structure of *G. arborea* is the same for both scenarios and it is concentrated in the 4^{th} age class. Comparing the area devoted to each ending age class for each species under both scenarios revealed differences. These differences in area are mainly due to the difference in species-site assignment as well as different risk-sensitive rotation ages called for under each scenario.

5.3.6 Growing stock at end inventory

The amount of growing stock left at the end of the planning horizon gives an indication at how harvests in previous working periods were conducted. Having an adequate volume of growing stock at end inventory suggests that previous harvests were not conducted in an exhaustive manner. It also assures that there is a substantial resource base on which future harvest decisions will be based upon.

The volume of growing stock at the end of the planning period for each compartment is shown in Figure 5.10. For both scenarios, there is an increase in the amount of growing stock from initial condition in majority of the compartments (15). However, comparing the total amount of growing stock from all compartments shows that under scenario 1 (201,802 m^3), there is a 15% reduction in the volume of the growing stock at end inventory from the initial condition (235,404). This reduction in growing stock is due to the fact that most of the compartments under scenario 1 are just past harvesting period resulting to younger or newly planted stands at the end of the planning period. The relatively young age class structure consequently results to lower growing stock volume. However, the 15% reduction still satisfies the set limits for fluctuation in harvests which is 20%. On the other hand, scenario 2 resulted to a 3% increase in the volume of growing stock from the initial condition, yielding an ending

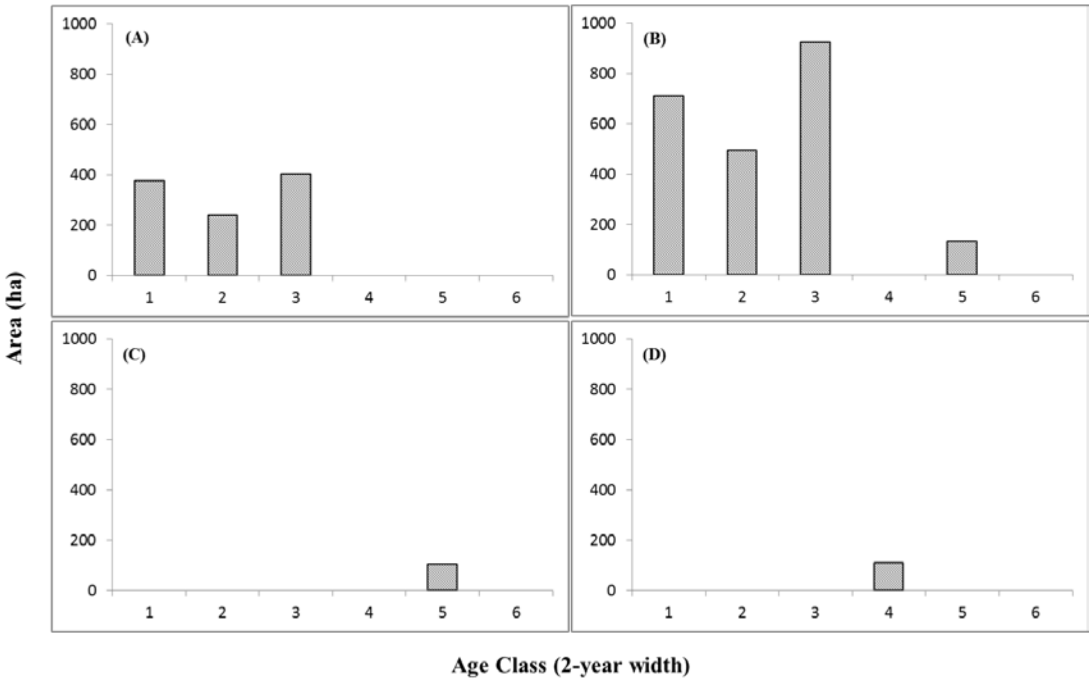

Figure 5.8 Ending age class structure under scenario 1 for (A) *P. falcataria*, (B) *E. peltatum* (C) *A. mangium* and (D) *G. arborea*

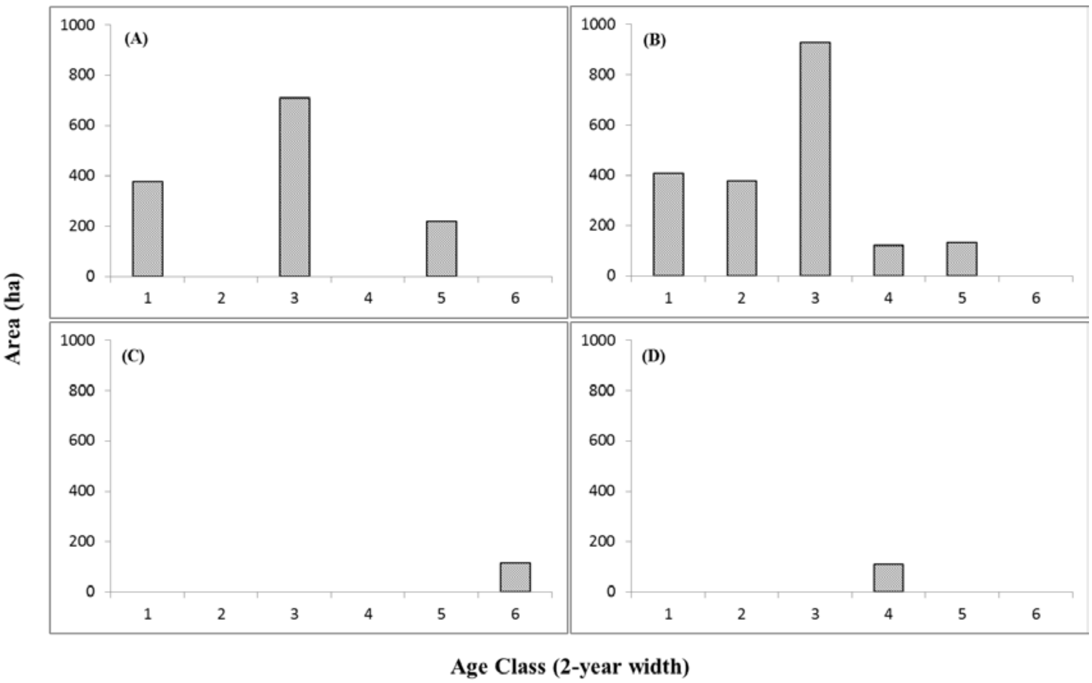

Figure 5.9 Ending age class structure under scenario 2 for (A) *P. falcataria*, (B) *E. peltatum* (C) *A. mangium* and (D) *G. arborea*

volume inventory of 241,752 m^3. The difference between scenario 1 and 2 is only 6,348 m^3, indicating that in both scenarios, sustainability of harvests from the plantation area is ensured.

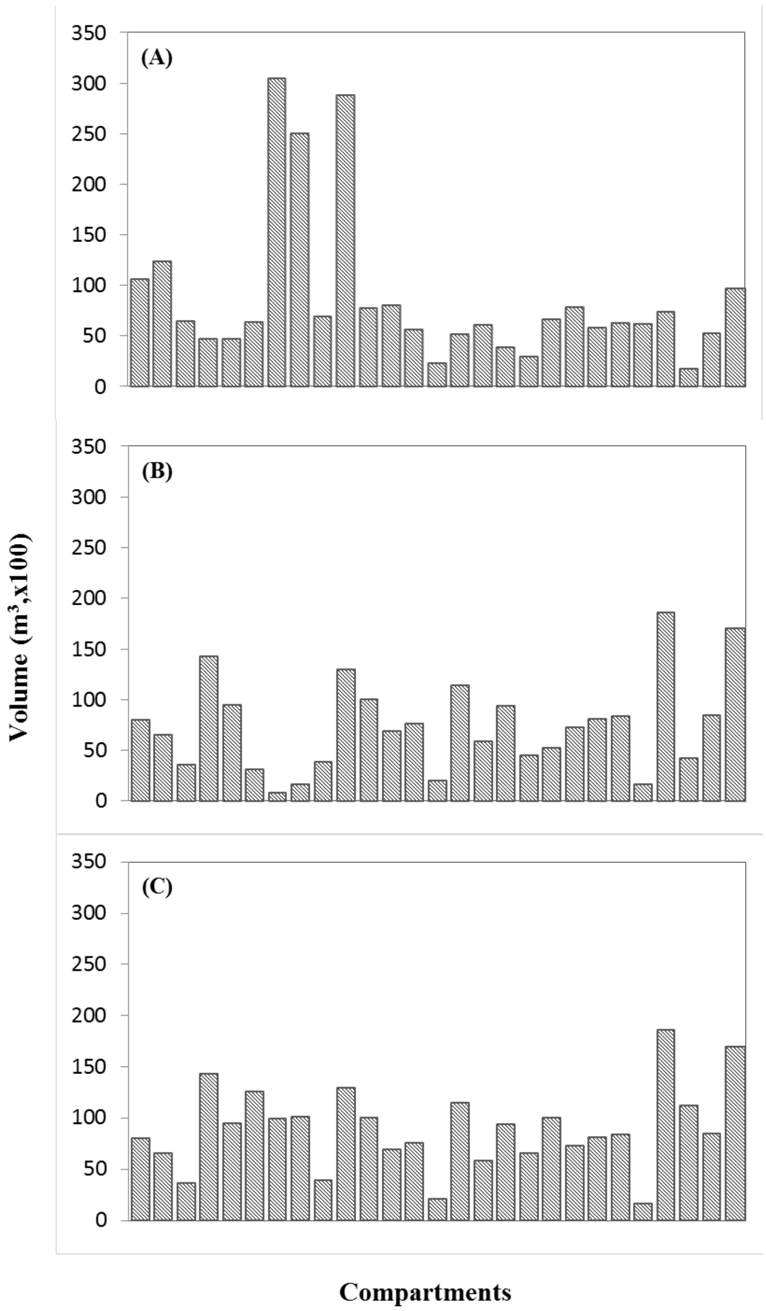

Figure 5.10 Volume of growing stock at each compartment at (A) initial condition and at the end of the planning horizon under (B) scenario 1 and (C) scenario 2

5.4 Discussion

The current management plan for the study area follows a systematic approach in scheduling harvests with the use of the area control method. However, decisions concerning the assignment of species to a management unit remain arbitrary. Due to its arbitrary nature, the attainment of maximum objective values in terms of timber volume production and NPV is not ascertained. In addition, though the study site has been experiencing past damages due to strong storms and typhoons, the current management plan has no provision to deal with the risk of damage, rendering it incapable to respond to such events. In order to resolve these issues and consequently improve how industrial tree plantations are managed, this study was conducted. The study introduced an approach to species-site assignment considering site productivity and risks while ensuring an optimal timber harvesting schedule that maximizes total volume of harvests and net present value.

5.4.1 Effects of management objectives on species-site assignment

The results of the species-site assignment models indicate that species assigned to a site may vary depending on the management objective. In the case of maximizing THV, the highest number of compartments and consequently area, are assigned to *E. peltatum* followed by *P. falcataria, A. mangium,* and *G. arborea.* However, switching objectives to maximizing NPV, increases the number of compartments allotted for *P. falcataria* while decreasing compartments and areas assigned to *E. peltatum* and retaining the same number of compartments for the other two species. The variation in species-site assignment between two management objectives suggests that the prioritization of species for each site depends on its volume growth and rotation age. In maximizing THV, *E. peltatum* is prioritized as it exhibits the highest volume growth among all species. In the case of maximizing NPV, areas allotted for longer rotation species are reduced to give priority to short rotation yet fast-growing species. In optimizing both management objectives, *E. peltatum* appeared to be of most priority as it can deliver good volume growth at short rotation periods.

The species-site assignment models suggest a level of prioritization among species depending on the objective. In the past, there were various attempts of the management to come up with the proper mix of species combination by prioritizing one species over the other. During the initial plantation establishment, *E. peltatum*, being a native species, was prioritized and the rest of the target species were secondary and planted only for the purpose of breaking monoculture. However, as time goes by and with the increasing popularity of *P. falcataria* in the region, the priority species being planted shifted from *E. peltatum* to *P. falcataria*. This is an indication that species prioritization is being practiced in the study site, but is executed without any optimization guidelines. The results of the study provided the information on what species should be prioritized on each site that will maximize THV and NPV. The results also imply that change in species priority decisions should not be done hastily but should be guided with some level of optimization to determine probable impacts on volume and profitability of future harvests.

The approach introduced in this study included risk considerations and proposed a way of minimizing risk and damage to sites by imposing shorter rotation ages on high-risk and medium-risk sites and use a longer rotation age for low-risk sites. Results show that under both scenarios, there is a tendency for optimal species-site assignment models to assign *P. falcataria* on high-risk sites and *E. peltatum* on low-risk sites. On high-risk sites, *P. falcataria* is to be managed on a short rotation period of 4 years. The prioritization of *P. falcataria* on these sites is attributed to its fast growth and ability to deliver relatively high volume even in short rotations. On the other hand, *E.peltatum* planted on low-risk sites is to be managed on a 9-year rotation period.

5.4.2 Trade-offs between management objectives

Hotvedt (1983) stated that generally decision-makers were not aware of the potential trade-offs associated with pursuing different goals. Choosing between the results of two management objectives entails a thorough investigation of the trade-offs in pursuing one objective over the other. Optimization results under the objective of maximizing THV and NPV both show high and sustainable volume production and profitability. Pursuing these objectives also results to ending age class structures which are better than initial conditions. The substantial amount of growing stock at the end of the planning period for both objectives ensure sustainability of potential future harvests. In the case of the study site which is managed under IFMA, lease could be renewed for another period whose length is 25 years. The volume of the growing stock is important particularly if the management decides to renew their lease, which is always the case.

In the objective of maximizing total harvestable volume, the optimal species-site assignment model results to a higher volume of harvests per working period, higher undiscounted net revenue giving a bigger value of total revenue at the end of the planning horizon. Pursuing this objective, however, may result to a flow of harvest that is less stable though mean deviation is kept at a value of 20% , higher fluctuations in net revenue from each working period and slightly lower volume of growing stock at end inventory.

On the contrary, optimization based on the objective of maximizing net present value results to a slightly lower value of total harvestable volume but leads to an increase in the total area harvested. Undiscounted net revenue and total revenue under this objective are lower, but the flow is more stable than in the first objective. Using the species-assignment model from this objective would also result to better long-term financial benefits of the plantation. In addition, pursuing this objective would result to higher volume of growing stock and more mature stands at the end of the planning period, both at the stand and individual species levels.

Comparing the two objectives showed that species-site assignment models are both feasible in terms of volume production and profitability with minimal differences. This shows that selecting any of the two objectives would lead to a level of high volume of harvests and NPV but at the expense of some trade-offs. In particular, the prioritization of long-term financial benefits over volume production would mean lower harvest volume and lower undiscounted revenue per working period. On the other hand, putting more consideration on volume production over net present value results to a less stable flow of harvest and income, lower amount of growing stock and less mature stands at the end of the planning period.

On top of these trade-offs, another difference in the species-site assignment models of the two management objectives lies on the sequence and schedule of forest management activities to be implemented. The optimal models dictate different risk-sensitive rotation ages for each species in each compartment and these demands difference in scheduling forest management activities. For example, rotation ages used in scenario 2 is generally shorter than in scenario 1 and these may call for more frequent implementation of intermediate treatments. In addition, longer rotations are imposed in scenario 1 and these mean longer exposure to other forms of risk, like fire and insect pests making it necessary for additional forest management activities related to safety measures.

The identification of the differences and trade-offs between the two management objectives would guide managers which alternative suits well to their management needs. In addition, the results of the optimization using the two objectives confirm that the flow of income and net revenue depends on the rise and fall of harvest volume per working period. This emphasizes that stability of harvest volumes is an important restriction in developing harvest schedules. In addition, it verifies the findings of other studies (Sedjo, 1984) that a higher NPV is achieved when plantations are managed at a shorter rotation periods.

5.4.3 Applicability of the optimal models

Results show that current species-site assignment is far from the optimal species-site assignment indicating that at current scenario the total potential of the site in terms of volume production and net present value is not being maximized. Considering the difference between the current and desired species-site assignment, the optimization models developed in this study presented how transition of the site's species assignment could be done in an optimal way.

In addition, at optimal condition considering a site's level of risk to damage, rotation ages could be shorter o longer than what is currently practiced. In using these rotations, profitability and volume production are all positive for all working periods and for both objectives. This will give the manager an assurance that even if the proposed rotation ages deviate from what is usually used; the primary considerations on volume production and profitability are still satisfied. Further, the implementation of new rotation regimes could be used as the basis for multiple-product decisions. In the case of the study area, timber produced are being used as raw material for various products such as veneer, pulp wood and lower value products such as wood pallets and match sticks. High-risk areas managed at a short-rotation could be assigned as permanent sources of raw material for low-value products which does not have big diameter requirements. On other hand, compartment managed at medium and long rotations could be designated for products requiring large diameter logs such as in the production of veneer and pulpwood.

In the Philippines, results of studies employing optimization techniques in designing timber schedules largely remained on paper and were not incorporated in management plans. The utility of these optimization models will only be realized if forest managers can incorporate them in real world planning and decision-making. Usually, these models are not used because of the level of difficulty by which the optimization process is conducted and secondly managers cannot visualize the plan particularly if they are limited to numerical plans and not converted into maps and visual plans. The study attempted to address these issues by introducing a simple and easy method of optimizing species-site assignment and timber harvest schedules and by converting the optimization results into a map. The maps showing the actual lay-out of species-site assignment based on the optimal models is an add-on to decision-making. Managers can visualize the results and this provides a venue for further analysis of potential problems arising from such species-site assignment and schedules. This could then be translated to objectives or constraints and further improve the models.

5.5 Conclusion

Prior to this study, forest management plans for industrial tree plantations in the Philippines follow a systematic manner and harvest schedules based on the empirical concept of area-control method. In this method, harvest areas are determined by dividing total plantation area by the desired rotation area with no considerations on site productivity. Issues also arise when designing a management plan for multi-species requiring different rotation periods. In the end, species-site assignment decisions for multiple species are done in an arbitrary manner without knowledge of its impact on over-all volume production and profitability. This study introduced an approach to optimizing species-site assignment using site productivity information and imposing rotation ages dictated by the site's level of risk to wind damage. Results of the study show that it is feasible to come up with species-site assignment models for a multi-species industrial tree plantation with a harvest schedule that altogether maximizes a management objective and satisfies restrictions on flow of harvest and income. Further, these models are applicable and could be used to guide timber harvesting decisions for multi-species plantations.

The study also concludes that the potential of the site in terms of volume production and net present value is not being maximized as the current species composition deviates significantly from the optimal species-site assignment models. It is suggested that the management rethinks and improves the management plans by integrating considerations on site productivity and risk and by applying some level of optimization.

The results of the study are not always certain and still needs further improvement. However, insights gained from the results could still be used as a basis for decisions related to harvest-scheduling or could be integrated into national plantation management strategy for multi-species plantation in the Philippines.

Chapter 6
Conclusions and Recommendations

6.1 Conclusion

In the Philippines, plantations are in the forefront of wood production in which more than 90% of annual log production depends on industrial plantations. However, issues and limitations emerged in reviewing past and current approaches used in plantation development and management. These issues and limitations may jeopardize the sustainability of plantations and consequently impact wood production in the country.

This study sought to address these limitations by introducing an approach to estimate site productivity from the ecological characteristics of the site, identifying the site's probability or risk of being damaged by strong winds from destructive storms and typhoons and by developing species-site assignment models that integrates site productivity and site risk. The species-site assignment models altogether maximize management objectives in the form of total volume of harvest and net present value and yield harvest-schedules that ensure a stable flow of future harvests.

Chapter 3 concludes that ecological factors mostly derived from DEM can be used to develop predictor models to estimate site productivity for different species. This demonstrated a practical yet scientific approach in estimating site productivity in a larger scale and for multiple species. Results showed that models resulting from multiple regression analysis were able to adequately estimate site index and site index variation for the four target species. Further, it is concluded that site productivity is limited by different ecological factors and their combinations, emphasizing the importance of species-specific site index models. Depending on the species, these factors may include elevation, wetness index, exposure to direct solar radiation, sunlight duration and amount of rainfall. In terms of practical issues, elevation can be used as a common variable to determine and differentiate site productivity in a multi-species or mixed-species plantation set-up. Also, it can be deduced from the site index map that site index variation exists across the site for the multiple species targeted. Forest managers can take advantage of this information in prioritizing species over limited areas.

The results of Chapter 4 conclude that stand-level factors such as average stand height, elevation, and topographic exposure significantly influence the occurrence of wind damage to plantation areas. The probability of damage exhibits direct relationship with stand-level variables whereby an increase in any of these variables will likely cause an increase in risk probability. This is relevant information as most plantations in the Philippines are situated in hilly and mountainous areas with rugged terrains but whose level of risks is unknown. Given the current terrain conditions, critical stand heights were computed to determine at which height level each site is rendered highly susceptible to damage. It is concluded that the majority of the site is classified at medium-risk levels while some other portions are at high and low-risk levels. The critical height levels serve as the basis for determining risk-sensitive rotation ages for specific sites at which species can be grown, thereby reducing risks of damage.

In chapter 5, it is concluded that is it feasible to come up with species-site assignment models that integrate site productivity and risk considerations. At the same time, these models were able to deliver timber harvest-schedules for multi-species that maximize management objectives while ensuring a stable supply of future harvests and income and adequate growing stock at the end of the planning period. Further, results conclude that pursuing different management objectives affect species-site assignment. In maximizing volume of harvests, *E. peltatum* is highly prioritized because of its good volume growth. On the other hand, in maximizing net present values, priority is given to shorter-rotations than relatively longer rotation species. In managing risks, results conclude that the plantation areas should be managed at generally shorter rotation periods than what is currently practiced. Also, models suggest that for high-risk sites, it is best to assign short rotations of *P. falcataria* regardless of the objective being maximized. Moreover, pursuing any of the two objectives would lead to sufficient harvests and profits but with the presence of some trade-offs.

This study attempted to introduce practical yet scientific approaches in addressing the limitations of plantation development and management in the Philippines. There were many issues related to plantation management, but this study narrowed down to resolving lack of site productivity estimates for species-site matching and inadequacy of management plans to consider risks of wind damage to plantations. The study demonstrated the possibility of including these two considerations in coming up with optimum species-site assignment models that guarantee the achievement of maximum objectives and stability of wood production. These results could provide the basis for harvest-scheduling related decisions and contribute to the science of managing industrial plantations in the Philippines.

6.2 Recommendations

Although the study was able to produce site index predictor models that can adequately estimate site productivity for certain species in Chapter 3, some limitations still exist. Only a number of ecological factors were considered in developing the models, and it is highly possible that in other areas, other factors may be considered significant and influential. It is recommended that for further improvement of site index estimation, other factors such as soil and soil-related characteristics are included. The study is also based on a limited area, but the approach can be implemented on a larger scale. In particular, higher resolution DEM is recommended for a national scale development of site index classification models for major plantation species. Further, it is recommended that future studies consider the use of stem analysis in determining site index of sample stands or trees for a more accurate model development.

In Chapter 4, the wind probability models included only three stand-level variables, it is recommended that other factors related to stand, site and wind characteristics are considered in further improving the models. In addition, the success of incorporating risks to management plans requires a reliable database of past stand attributes and damage estimations. It is, therefore, recommended that updating of models be conducted simultaneously with regular monitoring activities and increased post-damage inventory initiatives.

Finally, in Chapter 5, only two management objectives are analyzed but plantations could be managed for various purposes and objectives. It is therefore recommended that other objectives related to the function of the plantations like carbon sequestration, watershed values, biodiversity and others be considered in future optimization studies. In addition, the results of the study were patterned for an industrial scale plantation management, but the results and approach could be scaled-down or scaled-up to suit private farm level and community-based level plantations.

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