PRODUCTIVITY AND MORTALITY OF *Acacia mangium* Willd. PLANTATION WITH ASSOCIATED BARK BEETLE AND NITIDULID BEETLE IN EAST KALIMANTAN, BORNEO, INDONESIA

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by

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

PRODUCTIVITY AND MORTALITY OF *Acacia mangium* Willd. PLANTATION WITH ASSOCIATED BARK BEETLE AND NITIDULID BEETLE IN EAST KALIMANTAN, BORNEO, INDONESIA

presented by Muhamad Nurhuda Nugraha,

a candidate for the degree of Master of Science,

and hereby certify that, in their opinion, it is worthy of acceptance.

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Dedication

This thesis is dedicated to my parents and my wife who always pray for me

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All praise is due to Allah, Lord of the worlds. I would like to that to all the people who helped me making this research possible. I thank my advisor, Dr. Benjamin O. Knapp and my committee members, Dr. Rose-Marie Muzika, Dr. Deborah Finke, and Dr. Jeffery A. Wright, for their assistance and guidance in this research project. I also would like to thank to all the people at Araya Bumi Indonesia, especially Mr. Agus Kurnia Nugraha and Mr. Tan Wawie, for their full support on my master study. Thank also to Department of Plant Protection, Bogor Agricultural University, my almamater, who had provided me place and facility to work during my fieldwork in Indonesia.

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PRODUCTIVITY AND MORTALITY OF *Acacia mangium* Willd. PLANTATION WITH ASSOCIATED BARK BEETLE AND NITIDULID BEETLE IN EAST KALIMANTAN, BORNEO, INDONESIA

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Abstract

Acacia mangium Willd. is one of the most common tree species in industrial forest plantations in Indonesia. This tree species can grow rapidly in a wide range of soil conditions, and its wood properties are very suitable for the growing pulp and paper industry in the country. However, this tree species is also known to have high mortality due to tree diseases. Since 2011, 512 permanent sampling plots have been repeatedly measured to evaluate the development of *A. mangium* plantations in East Kalimantan. The sampling plots were established across a range of site conditions that varied in topography, soil physical characteristics, and soil nutrient content, as well as using different provenance and tree spacing. In this study we found that productivity and mortality of *A. mangium* in this area was comparable to other studies in humid tropical forest plantations, with survival 6 years after planting lower than 50%. The result of this study showed that provenance was an important variable in survival models of *A. mangium*. However, survival and mortality models that were developed in this study were not good enough to make prediction owing to irregular mortality in the study area, causing high variability in the dataset. There were trends on decreasing productivity and increasing mortality of *A. mangium* through time that might be related to *Ceratocystis* wilt. Log extraction identified some bark beetle and sap-feeding beetle that can be potential

insect vector of ophiostomatoid fungi and other pathogenic fungi on tree species. However, further study needs to be done to confirm if these beetles transmit the disease to *A. mangium* in the forest plantation in East Kalimantan, Borneo, Indonesia.

Chapter 1: Introduction

Acacia mangium (Fabaceae) is one of the most commonly used tree species in industrial forest plantations for pulpwood in Indonesia (Arisman and Hardiyanto, 2006; Awang and Taylor, 1993). The development of this industry in Indonesia was aligned with a government program with the goal to establish 2.3 million ha of industrial forest plantation by 2000 and 10.5 million ha by 2030 to fulfill the increasing demand of pulpwood in the country and worldwide (Arisman and Hardiyanto, 2006; Hardie et al., 2018a; The Ministry of Forestry of Indonesia, 2006). As a result of this massive program, Indonesia has been the largest producer of pulpwood in Southeast Asia since 1998, with *A. mangium* supplying the main product. In 2017, pulpwood production in Indonesia was about 35 million m^3 or 63% of the total production in this region (Food and Agriculture Organization of the United Nations, 2019), making Indonesia the 4th largest pulpwood producer in the world, after the United States, Brazil, and Russia.

A. mangium has become favored in many industrial forest plantations in Indonesia and other Southeast Asia countries because of its ability to grow rapidly across a wide range of soil and environment conditions (Hegde et al., 2013; Krisnawati et al., 2011) and its wood property is suitable for growing pulp industry in the country (Peh et al., 1982; Sahri et al., 1998). As a leguminous tree species, *A. mangium* can utilize rhizobia as symbiont within the nodules in the root systems to produce nitrogen. As a result, *A. mangium* can compete with most tropical weeds in the forest, including tenacious *Imperata* grasses, which usually become a big problem in many forest plantations in tropical regions (Krisnawati et al., 2011).

The productivity of *A. mangium* can be influenced by the silviculture practice applied in the plantation. Provenance, planting density, soil preparation, fertilization, and weed control are some of the factors that likely influence the growth rate of planted *A. mangium* (Hardiyanto et al., 2000; Vadez et al., 1995). Optimization of these factors can increase productivity. Stand characteristics such as slope, topography, and soil type can also affect the growth performance of the trees at the stand level (Hardie et al., 2018a; Nurudin et al., 2013a). In addition, productivity of *A. mangium* may be maintained or improved by suppressing mortality from pest and disease (Nambiar and Harwood, 2014). *Ceratocystis* wilt is one of the most important tree diseases in *A. mangium* plantations in Indonesia (Roux and Wingfield, 2009). Caused by Ophiostomatoid fungi, the disease can attack trees as young as 6 months old, resulting in potentially high mortality in the plantations. There have been reports that the dispersal of the fungi is helped by bark-beetles and sap-feeding beetles that were found commonly on infected trees (Gilbert, 2011; van Wyk et al., 2004; Zhou et al., 2006)

In East Kalimantan, Borneo, Indonesia, where many *A. mangium* plantations have been recently established, research on how age, silviculture practice, and soil quality influences the growth, mortality, and productivity of *A. mangium* is limited. This study develops survival and mortality models of *A. mangium* based on silviculture practices applied in the plantation. Given the potential for high levels of mortality, the mortality models may then be used to predict the productivity of *A. mangium* based on the silvicultural practice used for the upcoming rotation. Moreover, there are currently no available results from studies on bark beetles and sap-feeding beetles associated with Ophiostomatoid fungi in *A. mangium* plantation in East Kalimantan, Indonesia. Thus, we would like to identify potential insect vector(s) of *Ceratocystis* wilt associated with elevated mortality in *A. mangium* plantation.

This thesis is organized in three main chapters. First, we describe existing studies on productivity and growth rate of *A. mangium* in Southeast Asia, and the role of bark beetles and sap-feeding beetles as insect vector of *Ceratocystis* wilt disease in forest plantations. Second, we develop survival and mortality models of *A. mangium* at individual and stand levels in industrial forest plantations in East Kalimantan, Borneo, Indonesia and identify the mortality risk factors that can influence the productivity of *A. mangium* in the plantation. Third, we identify the bark beetle and sap-feeding beetle communities to describe potential insect vectors of *Ceratocystis* wilt disease in *A. mangium* plantation in East Kalimantan, Borneo, Indonesia.

Specific Objectives

Chapter 3 of this master thesis, **patterns and drivers of productivity and mortality in *Acacia mangium* forest plantation in East Kalimantan, Borneo, Indonesia,** describes research with the following objectives:

1. Describe the growth, productivity, and mortality of *A. mangium* in industrial forest plantation in East Kalimantan, Borneo, Indonesia,

2. Determine the changes in productivity and mortality of *A. mangium* through time in the plantation, and
3. Develop survival and mortality models of *A. mangium* in industrial forest plantation in East Kalimantan, Borneo, Indonesia.

Chapter 4 of this master thesis, **bark beetle and sap-feeding beetles associated with ophiostomatoid fungi in *A. mangium* plantation in East Kalimantan, Borneo, Indonesia,** describes research with the following objectives:

1. Compare and evaluate the diversity of bark beetle and sap-feeding beetles collected using two different method in *A. mangium* plantation in East Kalimantan, Borneo, Indonesia, and
2. Review bark beetle and sap-feeding beetle species that can be potential insect vector of *Ceratocystis* wilt disease in *A. mangium* plantation in East Kalimantan, Borneo, Indonesia

Chapter 2: *Acacia mangium*, *Ceratocystis* Wilt, and Associated Insects: A Review of Literature

Acacia mangium Willd. (Fabaceae) in Industrial Forest Plantation

Acacia mangium Willd is a leguminous tree species originally from Australia and eastern Indonesia. This tree species was first introduced in 1966 by Australian foresters to forest plantations in Malaysia as barriers of firebreak of trial plots for pine species (Kamis Awang and Taylor, 1993; National Research Council, 1983). However, this tree species was found to have good growth rate, even better than *Eucalyptus* spp. and *Gmelina* spp., which were the main tree species grown in the plantation. Within 5-10 years after introduction, *A. mangium* became popular, was grown extensively by many forest plantations in Malaysia, and spread to other tropical countries, including Indonesia (Arisman and Hardiyanto, 2006; Kamis Awang and Taylor, 1993; National Research Council, 1983).

The development of sustainable forest plantations in Indonesia was motivated by concerns with deforestation and unsustainable practice of wood extraction from natural forests in the country to fulfill the demand for tree products. Thus, the Indonesian government aimed a target to establish 10 million ha of forest plantation that can produce tree products sustainably by 2020 (Obidzinski and Dermawan, 2012; Samsudin, 2016). Since the establishment of forest plantations was focused on unproductive forest vegetation, often with productivity less than 16 m^3/ha and mostly covered by scrub and grasses, fast-growing trees such as *A. mangium* became the key in this national program (Potter and Lee, 1998). This tree species can grow even in degraded sites that lack nutrients and compete with serious tropical weeds such as *Imperata* grass, which usually is a big challenge in many agriculture and forest plantation areas (Arisman and Hardiyanto, 2006; Krisnawati et al., 2011; National Research Council, 1983).

In Indonesia, large-scale planting of *A. mangium* began in 1990 by private forest operations. The establishment of *A. mangium* plantations initially focused in Sumatra and later spread to Kalimantan to fulfill growing demand for pulp and paper in the country (Harwood and Nambiar, 2014). This operation was supported by the Ministry of Forestry of Indonesia, which had targeted 45 million tons of pulp production and 40.5 million tons of paper production annually by 2025 (Samsudin, 2016). Some of the forest operations also utilized *A. mangium* for particle board, crates, and woodchips, although it also had potential for sawn timber, molding, furniture and veneers (Kamis Awang and Taylor, 1993; Krisnawati et al., 2011).

Insect Associated with *Ceratocystis* Wilt

Ceratocystis sp. is an ascomycotan fungi that causes wilt disease in many trees. This disease is characterized by rapid wilt and death of trees. *Ceratocystis* infection was first described in 1890 on sweet potato in USA and is now well-known as important pathogens that cause of sap stain in timber. The *Ceratocystis* fungi are symbiotic associates of insects (de Beer et al., 2014). Two common insects reported to be vectors of *Ceratocystis* wilt disease include bark beetle (Coleoptera: Curculionidae) and sap beetle (Coleoptera:

Nitidulidae). In North America, *Ceratocystis* sp. was found to have association with *Ips* spp. bark beetles (Yearian, 1966). Similarly, associations have been found between Scolytinae bark beetle and blue stain fungi that causes wilting on Norway Spruce (Brignolas et al., 1998; Krokene and Solheim, 1996). The association between *Ceratocystis* and bark beetles was also reported in South Africa (Zhou et al., 2006) and Bhutan (van Wyk et al., 2004) on pine species. Similarly, sap-feeding beetles (Coleoptera: Nitidulidae) have been reported to be vectors of *Ceratocystis* fungi on many tree species (Appel et al., 1990; Hayslett et al., 2008; Heath et al., 2009).

Since first described, *Ceratocystis* has become one of the most important diseases in non-native *Acacia* plantation. The first report of *Ceratocystis* wilt infection in non-native *Acacia* species plantation was in Brazil (Ribeiro et al., 1988). Shortly after, there was a report of *Ceratocystis* sp. causing wilt and death on non-native plantation-grown *Acacia* in South Africa (Morris M. J. et al., 1993). Due to its pathogenicity, this disease is considered a major threat of timber production in plantations (Roux and Wingfield, 2009) and has reportedly caused mortality on many *A. mangium* trees in plantation in Sumatra (Tarigan et al., 2011a). However, there is still limited information on the extent of the problem and the association of the disease with insects, especially in East Kalimantan, Borneo, Indonesia.

Chapter 3: Patterns and Drivers of Productivity and Mortality in *Acacia mangium* Forest Plantation in East Kalimantan, Borneo, Indonesia

Introduction

Acacia mangium has played an important role in the development of forest plantations in Indonesia. Since its introduction from Australia to Malaysia in 1966, *A. mangium* has shown positive growth performance as a promising tree species that can grow fast in a wide range soil conditions (Kamis Awang and Taylor, 1993; National Research Council, 1983). Therefore, *A. mangium* has become the species of choice to plant in newly developed industrial forest plantations in Malaysia and surrounding countries. The massive development of sustainable forest plantations in Indonesia, which was altered by high rates of deforestation and unsustainable practices of wood extraction, made *A. mangium* a big part of the economy for the forestry sector in the country (ITS Global, 2011). This development was supported by the government of Indonesia, which set the goal to establish 10.5 million ha of sustainable forest plantations by 2030 (Obidzinski and Chaudhury, 2009; Samsudin, 2016).

Most *A. mangium* plantations in Indonesia are operated by private forest companies in the pulp and paper industry, with interest in understanding the productivity of this tree species for profit (Harwood and Nambiar, 2014). Productivity of *A. mangium* is commonly quantified as the volume of wood per hectare (ha), number of trees per ha, and mean annual increment at the end of rotation period. Beside the genetics of plant material, productivity of *A. mangium* is also influenced by the silvicultural practice and the physical environment where the trees are planted (Hardiyanto et al., 2000). In general, the optimum productivity of an individual tree can be achieved if the best possible genetics are supported by favorable environmental conditions, such as good soil quality, low stress from nutrient and water depletion, low competition from surrounding vegetation, and minimum threat from pest and disease.

However, for many forest operations, the future of *A. mangium* is still in question. Many forest operations have reported high mortality rates due to a range of biotic and abiotic factors. Poor seedling establishment and soil compaction due to the operation of heavy machinery have been identified as causes of low survival rates of *A. mangium* (Hardie et al., 2018a). The mortality rate was increasing as fully grown *A. mangium* trees were also found to be heavily damaged by windstorms. In addition, grasshoppers, crickets, and rodents can be common pests that cause mortality to seedlings and young *A. mangium* trees. As the trees grow older, the biotic threat increases with the presence of *Ceratocystis* wilt and *Ganoderma* root rot (Potter et al., 2006; Tarigan et al., 2011a). The buildup of inoculum of the pathogen and the spread by disease vectors may make these tree diseases more serious through time. In severely affected areas, mortality caused by these tree diseases can exceed 50% (Eyles et al., 2008; Hardie et al., 2018a; Mohammed et al., 2014; Roux and Wingfield, 2009).

Since research on productivity and mortality of *A. mangium* in forest plantations in East Kalimantan is limited, forest plantation companies are interested in understanding patterns of mortality in operational settings. In this study, the company has established hundreds of permanent sampling plots for inventory assessment with annual repeated measurement per individual tree. These data were integrated with the information of the provenance of the trees and soil condition that had been classified into several categories based on topography, physical characteristic, and nutrient content in each plot. From this dataset, we addressed several questions focusing on the development of *A. mangium* in this area to provide recommendations for plantation management, including developing survival and mortality models at the individual level and at the stand level. Specific study objectives included:

1. Describe the growth, productivity, and mortality of *A. mangium* in an industrial forest plantation in East Kalimantan, Borneo, Indonesia,
2. Determine the changes in productivity and mortality of *A. mangium* through time in the plantation, and
3. Develop survival and mortality models of *A. mangium* in an industrial forest plantation in East Kalimantan, Borneo, Indonesia.

Methods

Study Area and Data

The study area was an industrial forest plantation that is managed by PT. Fajar Surya Swadaya (PT.FSS) in East Kalimantan, Borneo, Indonesia (Figure 3.1). PT. FSS is an Indonesian private forest operation that was given legality by the Ministry of Forestry of Indonesia to manage 61,470 ha of concession area in East Kalimantan, Indonesia for industrial timber plantation based on Kepmenhut No. 282/Kpts-II/1997. With IUPHHK-HTI license No. SK. 428/Menhut-II/2012, this company started to operate in 2010 by planting *A. mangium* as their primary timber product for the pulp and paper industry, which was in line with national program to establish sustainable forest plantation as source of wood products. The production area of *A. mangium*, which was converted from a secondary forest that consisted of mixed hardwood, was only 50% of the total concession area. The rest of the concession area was maintained as secondary forest, conservation area, and livelihood crops as part of agreement with the Indonesian government.

The study area was located near the equator (116^{o}03’29.20” E to 116^{o}32’01.20” E and 1^{o}10’47.12” S to 1^{o}25’00.83” S). The climate of the study area was warm and humid year-round. Based on measurements from 2012 to 2015, the mean annual precipitation of the study area was 1918 mm, ranging from 1632 to 2618 mm, and the mean annual temperature was 26.7^{o}C, ranging from 17.7^{o}C to 38.0^{o}C. The elevation of the study area ranged from 10 to 286 m above sea level. In 2015, there were big fires in many forest areas in Indonesia, including East Kalimantan, and fire affected some parts of the study area at the concession area of the company.

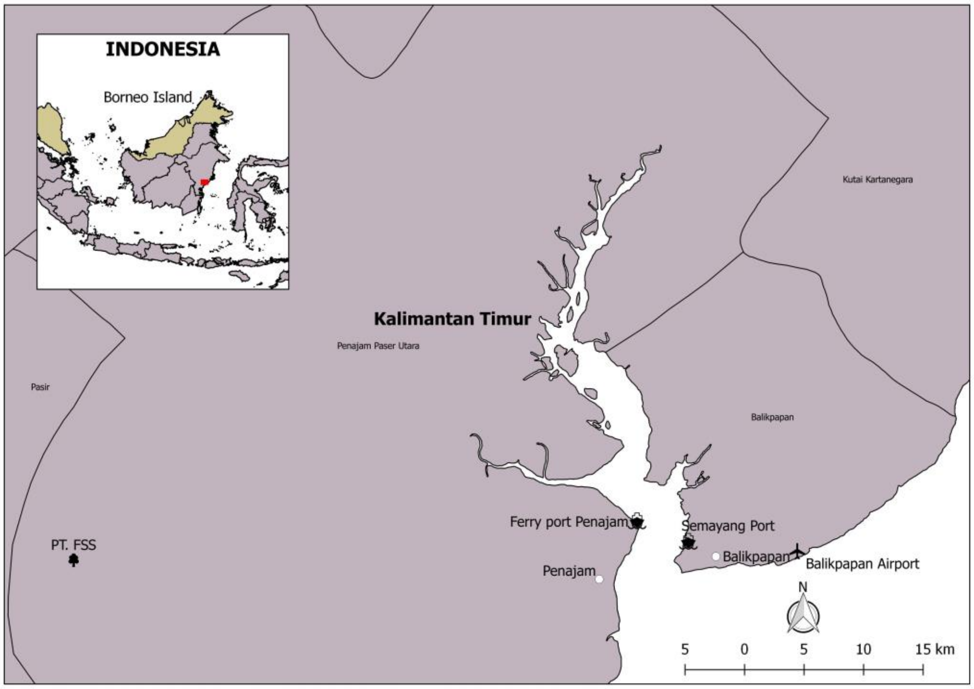

Figure 3.1. Location of study area in East Kalimantan, Borneo, Indonesia

A. mangium trees in the production area were planted as 3-month-old seedlings that were prepared in nursery area and then managed at the compartment level (± 25 ha). Planting density in the production area was 3 x 2.5 m^2 for planting before 2016 and 3 x 2 m^2 after 2016. One month before planting, the area was cleared of weeds with herbicide. To optimize tree growth and avoid competition from weeds, chemical weeding was also performed 1 month, 3 months, 6 months, and 12 months after planting. Basic fertilizer with potassium was applied to the planting hole during planting. One month after planting, any dead seedling was replaced with a new one. Singling the multiple leaders and pruning the branches of *A. mangium* were performed after 6 months of growth, before the heartwood was formed to maintain the full growth. However, these practices were not continued after 2016 due to concerns with creating introduction sites for wilt pathogen. The rotation period of *A. mangium* plantation in this forest company was 6 years. Once the trees were harvested, the planting area would be cleared again for new planting rotation.

There were 503 permanent sampling plots (PSP) established from 2011 to 2017 across the study area (Figure 3.2). There were different numbers of plots established in each year, depending on the planting area in each year, with each plot intended to represent 50 ha of the plantation area. Each plot was 512 m^2 and had a diamond shape. Each plot consisted of 80-120 trees, resulting in a total of 51,621 individual trees observed across the study area. The diameter at breast height (DBH) and total height of each *A. mangium* tree inside the plot were monitored and measured annually.

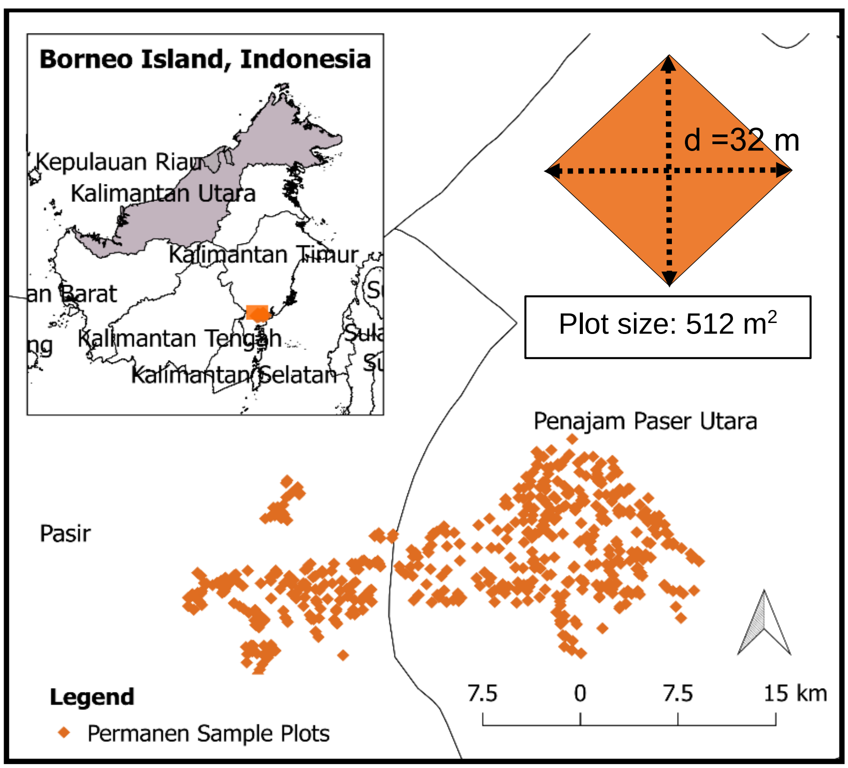

Figure 3.2. Distribution of permanent sampling plots (PSP) at PT. FSS

Statistical Analysis

We initially screened the measurement data from 2011 to 2017. Plots that were affected by the fire in 2015 were removed from the dataset for measurement data that took place after fire incidence, while the data from prior to the fire were maintained. We also excluded a few plots that were heavily damaged by wind. Plots with no recorded notes of fire or wind damage were maintained in the dataset, even when they had high mortality rate. In the dataset, there were some plots that had no information on soil characteristics. To avoid error and misinterpretation in statistical analysis, all observations that contained missing value were removed. We also excluded the plots that had mixed provenance from the dataset because each provenance might show different performance in term of growth and resistance against mortality agents.

There were 19 variables in the dataset, including 10 continuous variables and 9 categorical variables. In general, the variables could be categorized as four different types of information: information at the individual tree level, information at the stand level, spatial information, and temporal information (Table 3.1). There were 14 different provenances of *A. mangium* planted in the plots (Appendix 1). The provenance used were not consistent across the planting years, and the distribution of each provenance within the plantation depended on the availability at the nursery. The soils in the plots were categorized based on soil texture, soil chemical properties, and soil physical properties (Appendix 2).

Table 3.1. List of variables in the dataset

Variables	Notes
a. Individual level	
Tree status	Dead or alive
Diameter	DBH in centimeter
Height	Total height of the tree in meter
Volume	Individual tree volume in m^3
Age	Age after planting in years
Provenance	Origin place of the tree. There were 14 different provenances
b. Stand level	
TPH	No. of trees per ha
BA per Ha	Basal area per ha in m^2
Volume per Ha	Volume of trees per ha in m^3
No. of Dead Tree per Ha	No. of dead trees per ha
Soil Texture	Soil texture classification: FI (Fine), FL (Fine Loamy), Fsi (Fine Silty), VF (Very Fine)
Soil Physical	Soil physical classification: 1 (Well drain soils, deep to moderately deep soils, Fine particle size class), 2 (Well drain soils, deep to moderately deep soils, Fine loamy to fine silty particle size class), 4 (Well drain soils, deep to moderately deep soils, Very fine and fine particle size class), 6c (Low land, poorly drain soils, deep to moderately deep soils, Clayey, loamy, and silty particle size class)
Soil Chemical	Soil chemical classification: A (Enough P and K), B (Enough P, Less K), C (Less P, Enough K), D (Less P and K)
Elevation	Elevation of the plot in meter above sea level
Slope Class	Slope classification: 1, 2, 3, 4, 5, 6
c. Temporal	
Planting Year	In what year the tree was planted
d. Spatial	
Compartment	Compartment block where the tree was planted

Trend of Productivity and Mortality of A. mangium Over Time

Productivity and mortality of *A. mangium* in the forest plantation were compared at each age based on planting year from 2010 to 2016. To investigate if there were significant differences on volume of trees per ha, number trees per ha, and number of dead trees per ha at different planting year, one-way analysis of variance was performed in R version 3.5.1. Multiple comparison procedures by Tukey's were performed with in r-package "Agricole" for ANOVA with p-value < 0.05.

Survival Models of A. mangium at Individual Level

In this analysis, we used only measurement data of *A. mangium* trees with age from 1 to 5 years old to build classification tree-based models to predict if an individual tree was alive (1) or dead (0) in the following year of measurement. The dataset was divided randomly into 80% training dataset and 20% test dataset. We used tree-based method for classification analysis with the r-package "tree" to construct the decision tree from the training dataset. Gini index was used in the analysis to measure the total variance across the classification. When pruning the tree to lower tree complexity, we used cross-validation to know the size that had the lowest misclassification rate for the model. Random Forest analysis was also performed with "randomForest" r-package to increase the accuracy of the prediction, with 1,000 decorrelated trees produced and bootstrapped. Cross-validation on the number of variables used to construct each tree was performed to get the lowest misclassification rate of the model. Boosting method was performed with r-package “gbm” to produce 1,000 trees sequentially. In this method, each tree was grown using information from previously grown trees, where a decision tree was fit to the residuals from the model then added this new decision tree into the fitted function in order to update the residuals (James et al., 2013). By fitting the trees to the residuals, the prediction was slowly improved, especially in areas where it does not perform well. The shrinkage parameter (λ) slows the learning process of the model, allowing more and different shaped trees to decrease the residuals. The value of the shrinkage parameter in this method was decided using crossing-validation to achieve the lowest misclassification rate of the model.

In tree-based methods, error test rate and false positive rate from the confusion table were compared and evaluated. The confusion table included information on two types of errors in the classification: where the model incorrectly assigns an individual tree who is alive to the ‘dead’ category, or the model incorrectly assigns an individual who is dead to the ‘live’ category (James et al., 2013).

We also performed mixed-effect logistic regression to produce the equation of survival model. In this analysis, we created models with different combination of continuous variables and different categorical variables from the dataset. The value of AIC, error test rate, false positive rate, and the value of under area of ROC curve among the models were compared to determine the best model. Here, we expected to have AIC, error test rate, and false positive rate as low as possible, and value of under area of ROC curve as close as possible to 1.

Regression Model for Tree Mortality at Stand Level

In this analysis, we used measurement data of *A. mangium* trees with age from 1 to 6-years-old to build regression tree-based models to predict the number of dead trees per ha across the measurement age at the stand level. For model validation purpose, the dataset was divided randomly into 80% training dataset and 20% test dataset.

We used tree regression analysis in R by using r-package “tree” to produce a decision tree. In this analysis, we evaluated the test RMSE (Root Mean Square Error) of the model as parameter of model fitness. Cross-validation was used to decide the size of the regression tree that had the lowest mean square error (MSE). To improve the prediction, we performed Random Forest in R with “randomForest” r-package that produced 1,000 decorrelate trees and bootstrapped. To decide the number of variables used to construct each tree, we used cross-validation to get the lowest misclassification rate of the model. In this analysis, we could identify the important variables in tree classification based on the increasing value of node purity or the increase percentage of MSE. Boosting method was performed with r-package “gbm” to produce 1,000 trees sequentially, where each tree was grown by using residual information from previous grown trees to improve the prediction. The value of the shrinkage parameter in this method was decided using cross-validation to achieve the lowest test MSE of the model. In tree-based methods, error test rate and false positive rate were compared and evaluated.

We also performed mixed-effect regression analysis to develop a model equation to predict the number of dead trees per ha across the measurement age at the stand level. Different linear model and non-linear model equations were produced in this analysis to choose the best fit model. The parameters used for the model comparison including the value of R-squared and value of test RMSE.

Results

Growth, Productivity and Mortality

In one-year-old plots, the average total height of *A. mangium* was 4.50 m and the average DBH was 5.60 cm. At six years, the average total height reached 20.27 m and average DBH was 19.33 cm (Table 3.2). The tallest tree recorded in the plots at age 6 was 26.70 m, and the biggest DBH recorded in the plots was 30.30 cm. All the data in the dataset were from plots in the first planting rotation.

Table 3.2. Average DBH (cm) and total height (m) of individual *A. mangium* stands in 503 permanent sampling plots

Statistics	1 year old (503 plots)	2 years old (394 plots)	3 years old (284 plots)	4 years old (241 plots)	5 years old (178 plots)	6 years old (64 plots)
No. of observation	38,781	30,537	21,694	18,269	13,731	5,106
DBH (cm)						
mean	5.60	9.82	12.44	14.55	16.28	19.33
stdev	1.07	1.02	1.20	1.51	1.72	2.69
max	9.50	14.36	17.89	20.05	25.15	30.30
min	2.92	7.25	9.58	11.80	12.92	14.65
Height (m)						
mean	4.50	8.72	12.04	14.79	17.62	20.27
stdev	0.76	1.07	1.13	1.40	1.72	2.20
max	6.95	11.84	15.25	21.11	22.97	26.70
min	2.26	5.38	9.03	11.37	13.96	10.50

Productivity of *A. mangium* in industrial forest plantation is determined by three factors: the number of trees per hectare, volume of trees per hectare, and mean annual increment (MAI). Based on observation on 503 permanent sampling plots that were established from 2011 until 2017, the average number of trees per hectare at planting was 1,509 and declined to 618 trees per ha at age 6 (Figure 3.3). The average volume of trees per hectare at age 6 years old was 158.4 m^3/ha (Figure 3.4). The MAI increased from age 1 to 4, until it reached 29.08 m^3/ha/year and began to decrease to 26.40 m^3/ha/year at age 6 (Figure 3.5). The highest MAI of *A. mangium* in the plantation was 56.74 m^3/ha/year at 4 years old and the lowest was 0.76 74 m^3/ha/year at 6 years old.

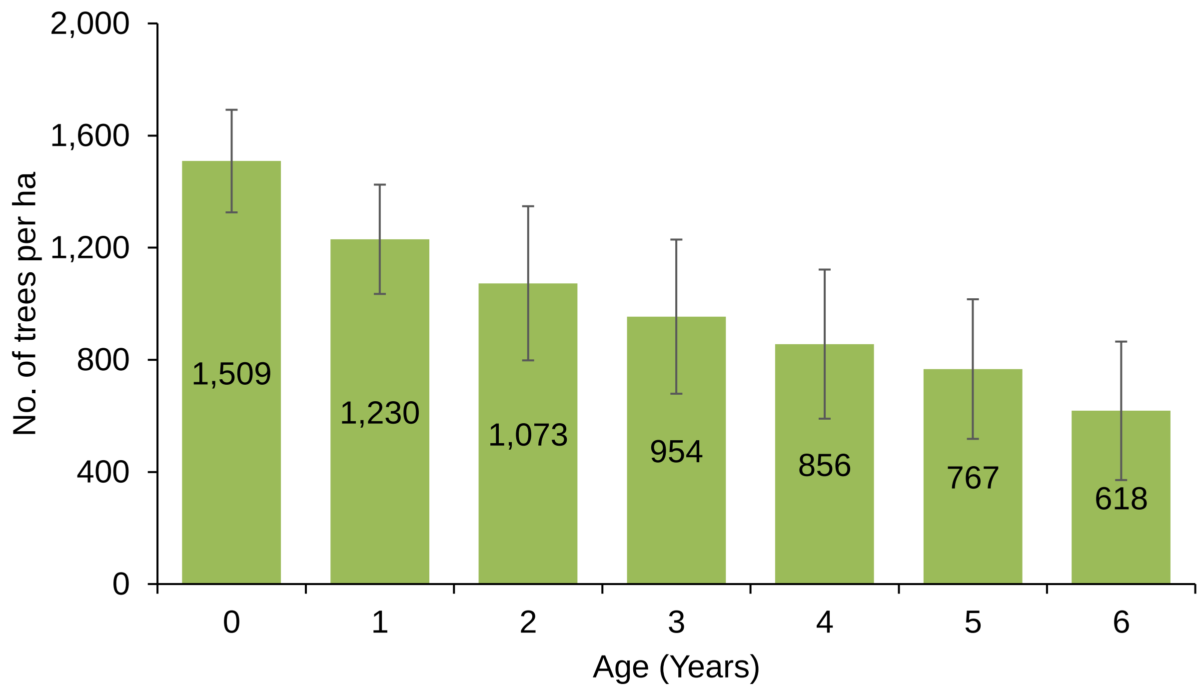

Figure 3.3. Average number of *A. mangium* trees per hectare with standard deviation in industrial forest plantation in East Kalimantan, Borneo, Indonesia

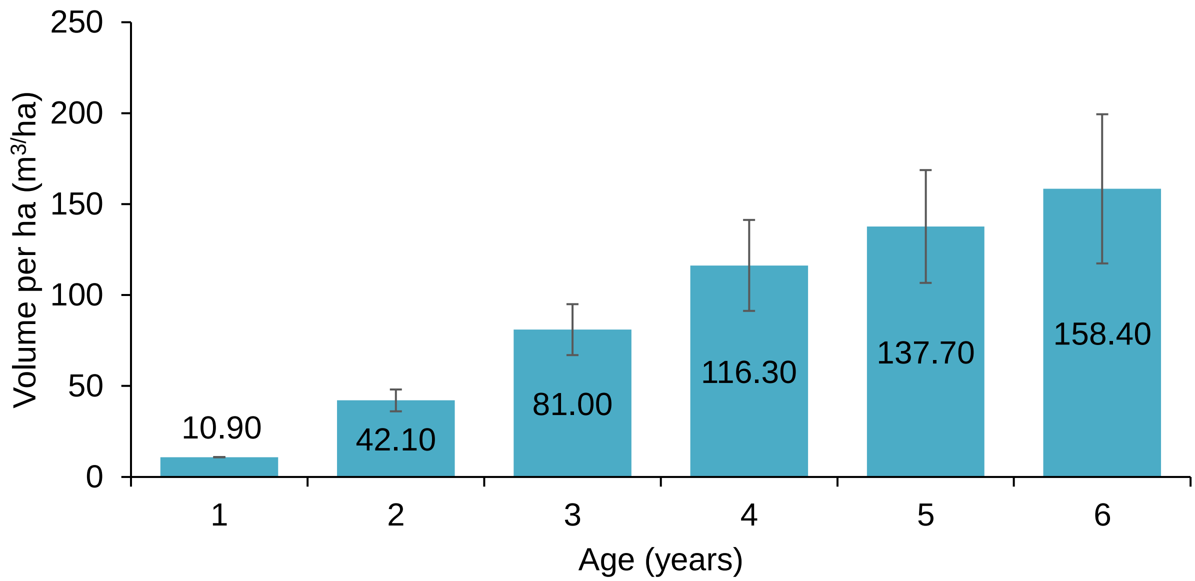

Figure 3.4. Average volume of *A. mangium* trees per hectare (m^3/ha) with standard deviation in industrial forest plantation in East Kalimantan, Borneo, Indonesia

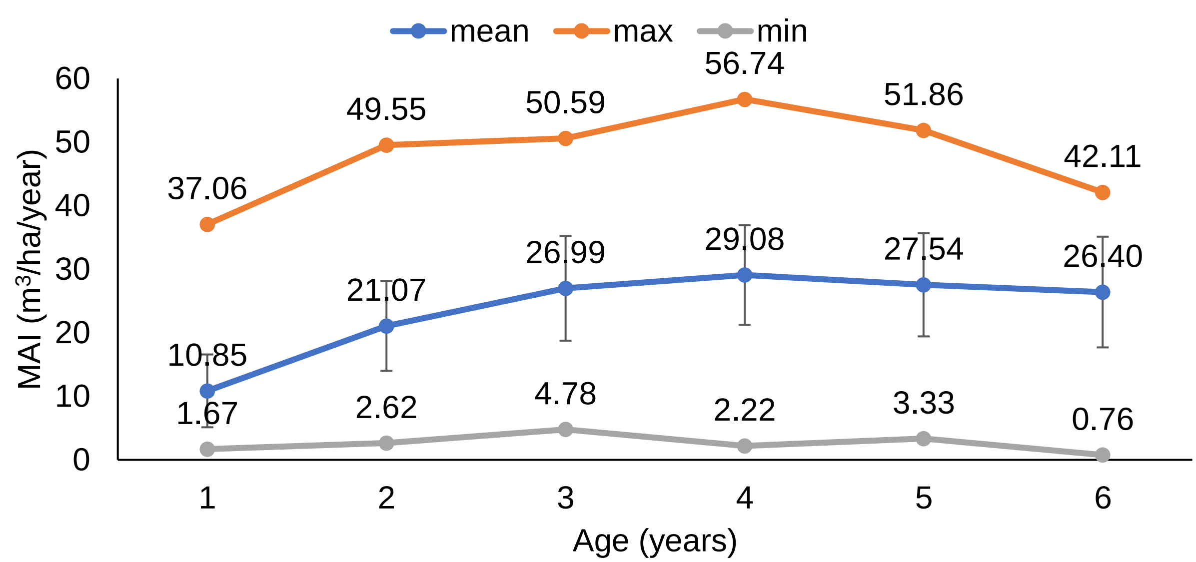

Figure 3.5. Maximum, minimum, and average mean annual increment (MAI) of *A. mangium* (m^3/ha/year) with standard deviation in industrial forest plantation in East Kalimantan, Borneo, Indonesia

The average survival rate 1 year after planting was 82% and kept decreasing each year. At the end of rotation period, the survival rate was only 39% (Figure 3.6). The annual new mortality rate differed through time. The highest new mortality rate was recorded in the first year, when 18% of planted seedlings died (Figure 3.7). After that, the new mortality rate decreased to 11% from age 1 to 2 years old. Since then, the new mortality rate was relatively constant each year ranging from 10% to 12%.

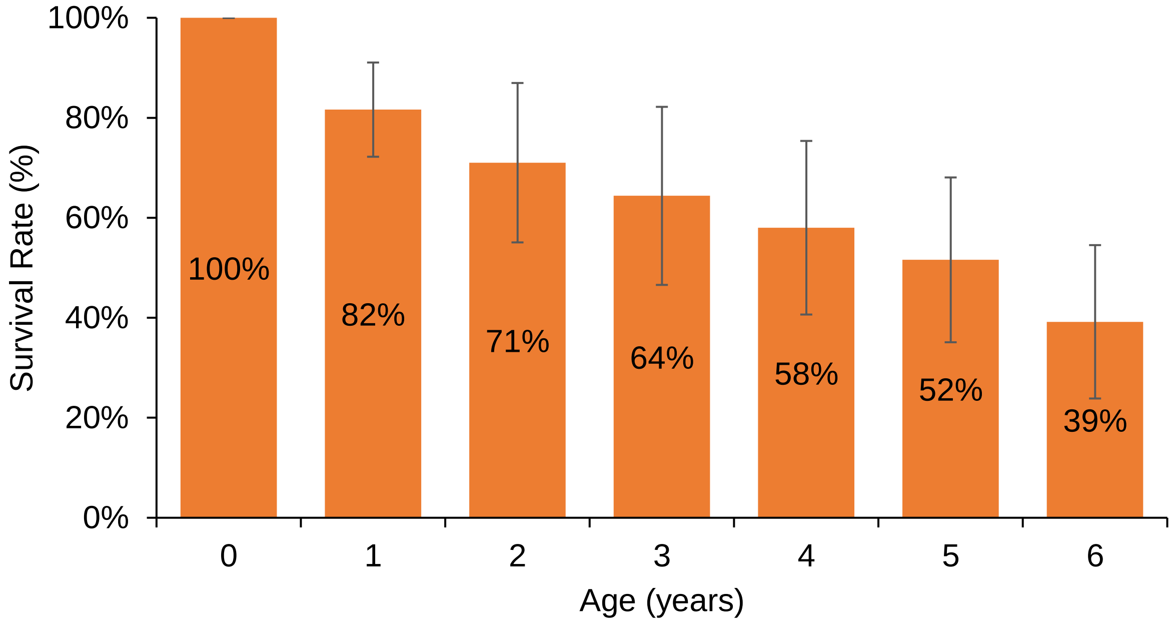

Figure 3.6. Average survival rate of *A. mangium* with standard deviation in industrial forest plantation in East Kalimantan, Borneo, Indonesia

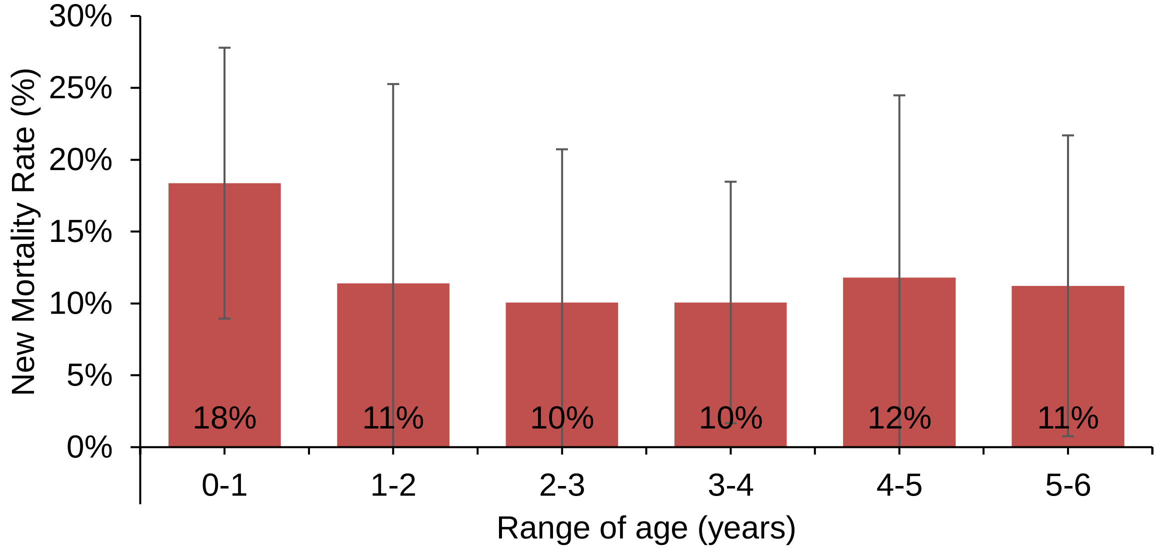

Figure 3.7. Average new mortality rate of *A. mangium* at different age with standard deviation in industrial forest plantation in East Kalimantan, Borneo, Indonesia

Trend of Productivity and Mortality of A. mangium in Forest Plantation

ANOVA results demonstrated that there was statistical evidence at 95% significance level that the average volume of trees per hectare and the average number of trees per hectare at a given age differed by planting year (Appendix 3 and 4). The standing volume per ha was greater in earlier plantings from 4-year-old stands through 6-year-old stands, with lower volume at the same age for more recent plantings (Table 3.3). This pattern was also evident from age 3 for the number of trees per hectare. There was a trend of increasing number of dead trees per ha at different planting age. The pattern became clear at age 3, at which time the number of dead trees per ha was greater for the trees that were planted in more recent years compared to trees that were planted in the previous year (Figure 3.8).

Table 3.3. Average volume and number of *A. mangium* trees per hectare based on planting year in industrial forest plantation in East Kalimantan, Borneo, Indonesia

Planting Year	Age (years)						
	0	**1**	**2**	**3**	**4**	**5**	**6**
a. Volume per ha (m^3/ha)							
2010	0 ± 0	6.9 ± 2 d	42.1 ± 12 ab	86.8 ± 24 a	131.8 ± 30 a	144.7 ± 34 a	181 ± 44 a
2011	0 ± 0	8.9 ± 4 d	46.8 ± 13 a	91.8 ± 20 a	124.6 ± 26 a	139.8 ± 41 a	146.5 ± 53 b
2012	0 ± 0	10.3 ± 5 cd	43.5 ± 13 ab	70.8 ± 20 b	96.7 ± 26 b	104.4 ± 38 b	
2013	0 ± 0	12.9 ± 5 b	38 ± 15 b	54.4 ± 21 c	67.3 ± 36 c		
2014	0 ± 0	11.2 ± 4 bc	30.7 ± 12 c	35.5 ± 14 c			
2015	0 ± 0	12 ± 7 bc	43.8 ± 15 ab				
2016	0 ± 0	23.1 ± 9 a					
b. No. of trees per ha							
2010	1520 ± 192 abc	1239 ± 205 bc	1221 ± 199 a	1061 ± 201 a	950 ± 202 a	838 ± 182 a	717 ± 213 a
2011	1486 ± 188 bc	1241 ± 170 b	1173 ± 184 a	1078 ± 187 a	962 ± 190 a	777 ± 248 a	566 ± 250 b
2012	1440 ± 182 c	1117 ± 210 c	962 ± 208 bc	832 ± 234 b	611 ± 225 b	539 ± 250 b	
2013	1636 ± 221 a	1354 ± 246 a	1088 ± 364 a	631 ± 304 c	463 ± 310 b		
2014	1486 ± 141 bc	1201 ± 155 bc	837 ± 306 c	371 ± 90 c			
2015	1553 ± 129 ab	1257 ± 159 b	1071 ± 242 ab				
2016	1430 ± 112 c	1189 ± 149 bc					

Note: Groups according to probability of means differences and alpha level (0.05) in Tukey Test

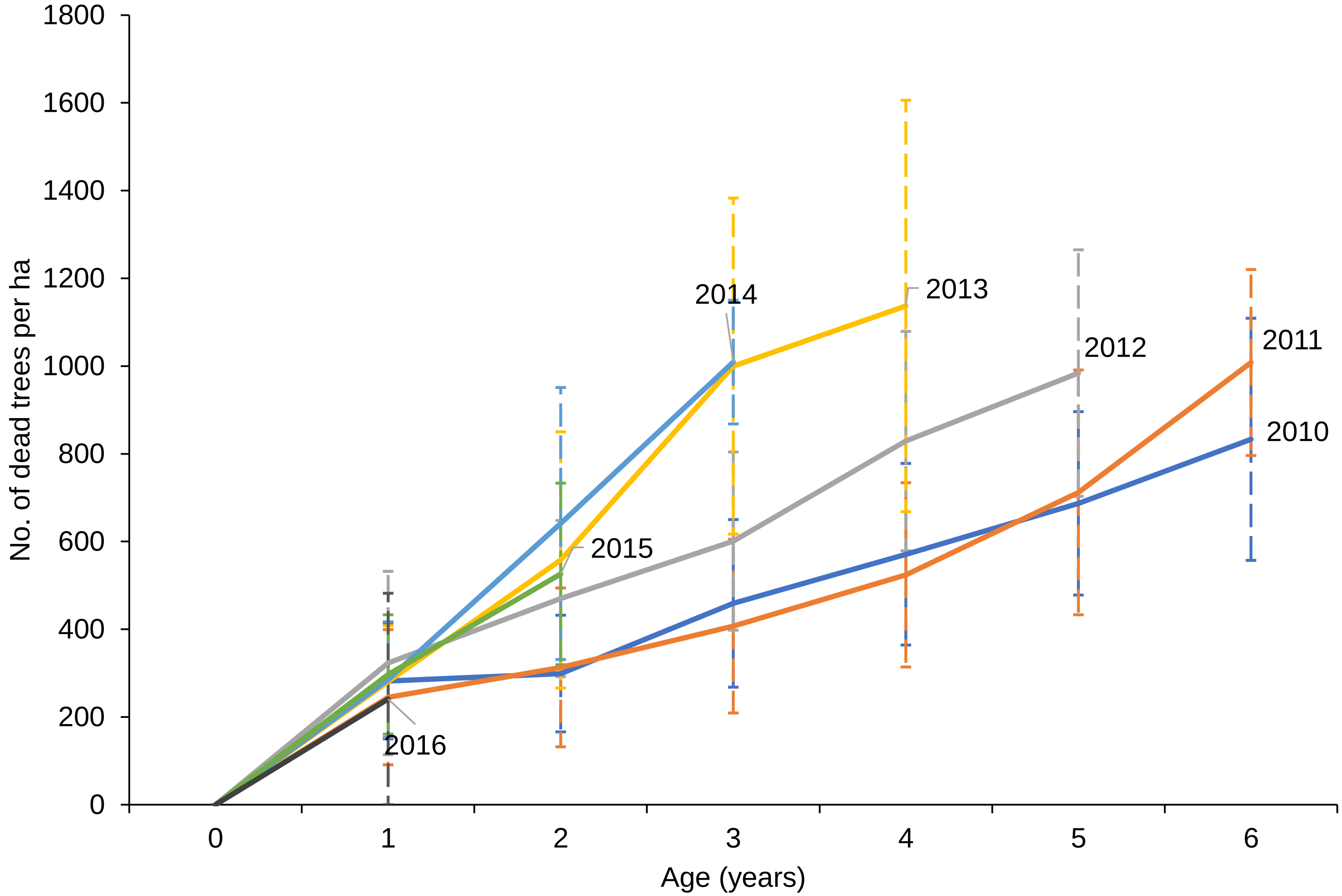

Figure 3.8. Average no. of dead trees per ha with standard deviation based on planting year in industrial forest plantation in East Kalimantan, Borneo, Indonesia

Survival Model of A. mangium at Individual Level

Survival models of *A. mangium* at the individual level were developed using three tree-based methods and a mixed-effect logistic regression. From 19 predictors variables available in the dataset, there were only 14 predictors variables used. Information on DBH, volume per ha, measurement age, number of dead trees in the plot, and plot number (PSP), were excluded because these five predictors had Pearson's correlation value > 0.90 and had VIF value more than 15 (Appendix 6 & 7). The removal of those variables was necessary to avoid collinearity in the models.

The first tree-based method using tree classification with the Gini index in each split resulted in a decision tree with 3,335 terminal nodes. The test error rate of this model was 16.39% and the residual mean deviance was 0.4449 (Table 3.4). Each split in the decision tree belongs to the most commonly occurring class of training observations in the region to which it belongs. The decision tree was pruned to reduce its complexity. Cross-validation of the model showed that the deviance was minimum started from a three-node-tree (Appendix 8).

Table 3.4. Model evaluation of tree classification before and after pruning

Tree Classification	No. of Terminal Node	Residual Mean Deviance	Test Error Rate	False Positive Rate
Before pruning	3,335	0.4449	16.40%	66.33%
After pruning	5	0.8161	15.85%	92.29%

The simplest pruned-decision tree contains five terminal nodes using three variables in tree construction: provenance, planting year, and soil chemistry (Figure 3.9). The top internal node corresponds to splitting based on provenance, with the left-hand branch coming out of that node including observations with trees with provenance C.Siro, Deri-deri, Muting, P. Panjang, Sebuhur, and Subanjeriji, while the right-hand node consists of the remaining tree provenance. The text Soil: A, B, C two splits down the tree at the left indicates that provenance Muting and P. Panjang that were planted in 2013 and 2014 with soil chemical classification: A (Enough P and K), B (Enough P, Less K), C (Less P, Enough K). However, it is also necessary to evaluate the model by looking at the misclassification rate of the model.

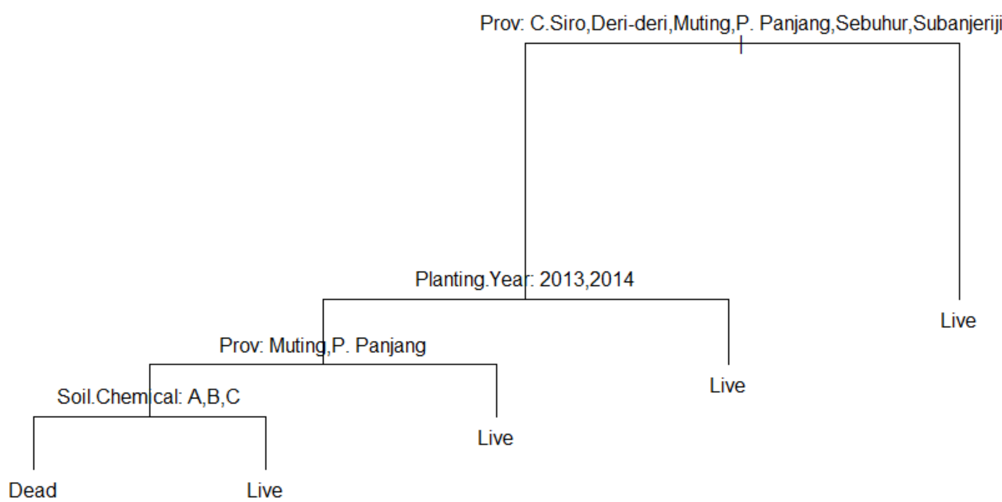

Figure 3.9. A decision tree of tree classification method after pruning

A confusion matrix was generated to compare the observed and predicted values to determine the congruence of the model classification with the field data (Table 3.5). Confusion table of pruned-tree classification model showed that the model predicts

10,115 individual trees would live and 210 individual trees would be dead in the following year (Table 5). In this model, 8,688 trees were correctly predicted, where 8,558 trees were actually live, and 130 trees were actually dead. It means that 84.15% prediction of the model was correct, so the test error rate was 15.85%. Out of 8,638 of the individual live trees, there were only 80 trees were incorrectly labeled. However, there were 1,557 of the 1687 individual trees were misclassified as live by the model. From the perspective of the company, 1,557 of 1,687 or 92.29% false positive rate of the model was unacceptable because the high number of trees that were predicted to live in the following year were actually dead.

Table 3. 5. A confusion matrix compares the prediction and the true status of individual *A. mangium* in the following year using pruned-tree classification model

		True Tree Status		
		Dead	Live	Total
Predicted Tree Status	Dead	130	80	210
	Live	1,557	8,558	10,115
	Total	1,687	8,638	10,325

The second tree-based method was Random Forest, where 1,000 of decision trees were built in bootstrapped training dataset and combined to create a single predictive model. In this method, each split in a decision tree consider only one predictor variable from random sample of predictors (*m*) of full set predictors (*p*) in the dataset. This method did not allow consideration of the dominant variables in the dataset and created decorrelated-trees instead to increase the accuracy of the prediction (James et al., 2013). Based on cross-validation of the model, 3 samples of predictor variables in each split resulted in the lowest error test rate (Appendix 9). Random Forests method resulted in model with test error rate 13.86%, where the model predicts incorrectly 262 live trees and 1,169 dead trees in the following year from a total 10,325 predictions (Table 3.6). The false positive rate of this model was 69.29%, where 1,169 of 1,687 dead trees were misclassified. Although these misclassification rates were lower compared to tree classification method, the false positive rate was still high and indicated that the model was still not good enough to predict dead trees.

Table 3.6. A confusion matrix compares the prediction and the true status of individual *A. mangium* in the following year using Random Forests method

		True Tree Status		
		Dead	Live	Total
Predicted Tree Status	Dead	518	262	780
	Live	1,169	8,376	9,545
	Total	1,687	8,638	10,325

The third tree-based method was Boosting, where 1,000 trees were produced sequentially and combined to create a single predictive model. Based on the cross-validation of the model, the lowest misclassification rate could be achieved by setting the value of shrinkage parameter to 0.104 (Appendix 10). The Boosting method in this study resulted a model with test error rate 13.98%, where 1,234 dead trees and 209 live trees were incorrectly predicted by the model (Table 3.7). The false positive rate of this model was 73.15%, where 1,234 of 1,687 dead trees were misclassified. The high value of false positive rate was still above the expectation and indicate that the model was not good enough to predict the dead trees.

Table 3.7. A confusion matrix compares the prediction and the true status of individual *A. mangium* in the following year using Boosting method

		True Tree Status		
		Dead	Live	Total
Predicted Tree Status	Dead	453	209	662
	Live	1,234	8,429	9,663
	Total	1,687	8,638	10,325

Since a large number of trees were produced in this method, it is no longer possible to represent the result in a single decision tree. However, the overall summary of importance variables can be obtained by looking at the mean decrease in Gini index of each variable, relative to the largest (James et al., 2013). The relative influence plot of Boosting method showed that there were five predictors variables in the dataset that had high relative influential values: measurement age, volume, basal area per ha, provenance, and height (Figure 3.10). In this case, we might expect that the probability of *A. mangium* to live in the following year is decreasing as the increasing of age, volume of individual tree, basal area per ha, and height. These results suggest that provenance might give different probability of tree survival. In this model, soil texture and soil physical were identified as the least influential variables in the model.

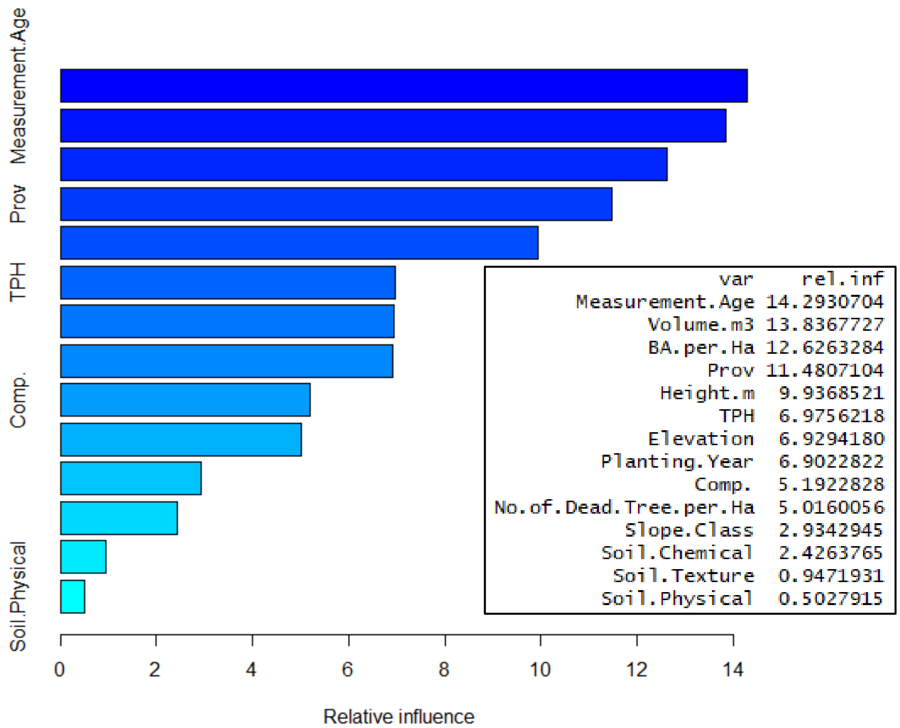

Figure 3.10. Relative influence plot of Boosting method in survival model of *A. mangium* at individual level

There were 14 different models built using mixed-effect logistic regression (Appendix 11). The 12th model, glmr12, was considered better than the other models because it had the lowest AIC value (28,760), test error rate (14.27%), false positive rate (76.35%) and the highest AUC of ROC (0.803). The fixed effects in the model included height (m), volume of individual tree (m^3), basal area per ha (m^2/ha), and number of dead trees per ha and the interactions between them, while provenance and planting year were addressed as mixed effect in the model. Measurement at different age was addressed as temporal pseudo-replication in the model, and compartment and plot number were addressed as spatial pseudo-replication with nested design. All the coefficients in the model were significant except the intercept and interaction between height and basal area per ha, where p-value > 0.05 (Table 3.8).

Table 3.8. Coefficients and significance of predictor variables in glmr12 model

Fixed Effect	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	0.7765	0.7019	1.1063	0.2686164
Height.m	0.3350	0.0325	10.3153	6.01E-25
Volume.m3	29.8227	5.6343	5.2930	1.20E-07
BA.per.Ha	-0.2094	0.0199	-10.5137	7.47E-26
No.of.Dead.Tree.per.Ha	-0.0009	0.0004	-2.0198	0.043409
Height.m:Volume.m3	-1.9340	0.2799	-6.9094	4.87E-12
Height.m:BA.per.Ha	0.0030	0.0022	1.3837	0.166453
Volume.m3:BA.per.Ha	-1.3345	0.3487	-3.8277	0.000129
Height.m:No.of.Dead.Tree.per.Ha	0.0004	0.0001	5.8984	3.67E-09
Volume.m3:No.of.Dead.Tree.per.Ha	-0.1179	0.0091	-12.9838	1.51E-38
BA.per.Ha:No.of.Dead.Tree.per.Ha	0.0007	0.0001	10.8869	1.33E-27
Height.m:Volume.m3:BA.per.Ha	0.0802	0.0156	5.1283	2.92E-07
Height.m:Volume.m3:No.of.Dead.Tree.per.Ha	0.0056	0.0004	13.0024	1.19E-38
Height.m:BA.per.Ha:No.of.Dead.Tree.per.Ha	-0.0001	0.0000	-19.3901	9.36E-84
Volume.m3:BA.per.Ha:No.of.Dead.Tree.per.Ha	0.0090	0.0004	20.2985	1.33E-91
Height.m:Volume.m3:BA.per.Ha:No.of.Dead.Tree.per.Ha	-0.0004	0.0000	-27.9073	2.18E-171

Significant codes: 0 '***', 0.001 '**', 0.01 '*', 0.05 '.', 0.1 ' ', 1

Mortality Model of A. mangium at Stand Level

Mortality models of *A. mangium* at the stand level were developed using three tree-based methods and mixed-effect regression. The number of dead trees per ha was predicted using 10 predictor variables: basal area per ha, age (years), provenance, soil texture, soil physical, soil chemical, elevation slope class, planting year, and compartment. The value of generalized variance inflation factors with dimension adjustment of predictor variables in the model were below 5, which means there was multicollinearity in the model (Appendix 12).

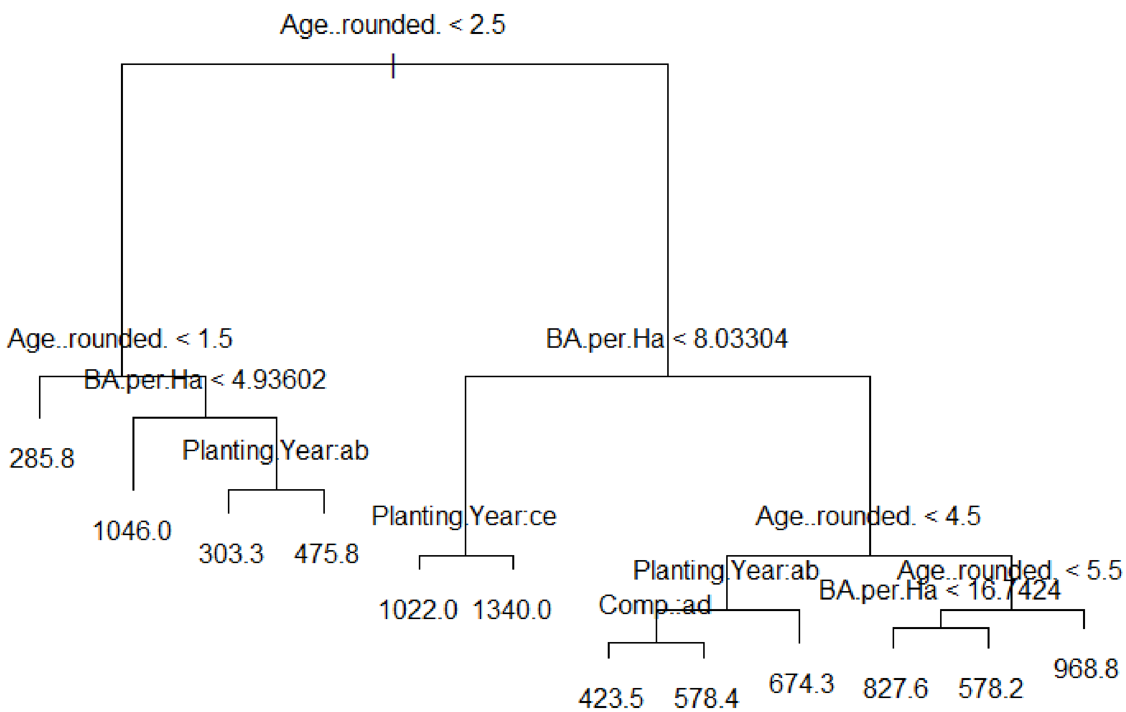

Figure 3.11. A decision tree of tree regression analysis

The first tree-based method using tree regression analysis resulted in a decision tree with 11 terminal nodes that were constructed using four predictor variables: age (years), BA per ha, planting year, and compartment (Figure 3.11). The regression tree consisted of a series of splitting rules, staring at the top of the tree. The top split assigned the trees less than 2.5-years-old to the left branch and trees older than 2.5 years to the right branch. On the right branch, the group was further subdivided by basal area per ha. Stands having basal area less than 8.03 m^2 per ha go to the left branch. This group was than subdivided again with planting year, where the trees that were planted in year c and e, which meant 2012 and 2014, were likely to have 1022 dead trees per ha, and the others were likely to have 1340 dead trees per ha. The test RMSE of this model was 198.38 (Figure 3.12). This indicated that this model leads to test predictions that were around 198 dead trees per ha of the true median.

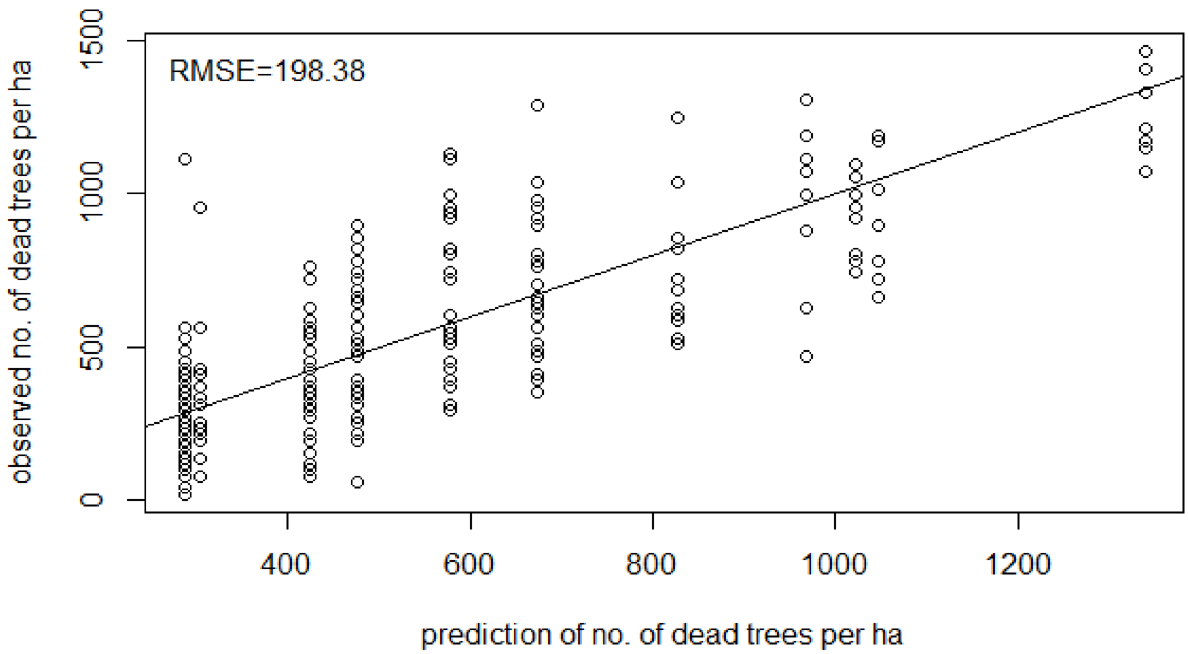

Figure 3.12. Prediction and observed of no. of dead trees per ha with tree regression

The second tree-based method was Random Forest, where 1,000 of decision trees were built in bootstrapped training dataset and combined to create a single predictive model. Based on cross-validation of the model, 5 samples of predictor variables in each split resulted in the lowest MSE (Appendix 13). Random Forests method resulted in model with test RMSE 165.34, which was lower compared to tree regression (Figure 3.13). However, this value is still considered high for the mortality model that predict number of dead trees per ha in *A. mangium* plantations.

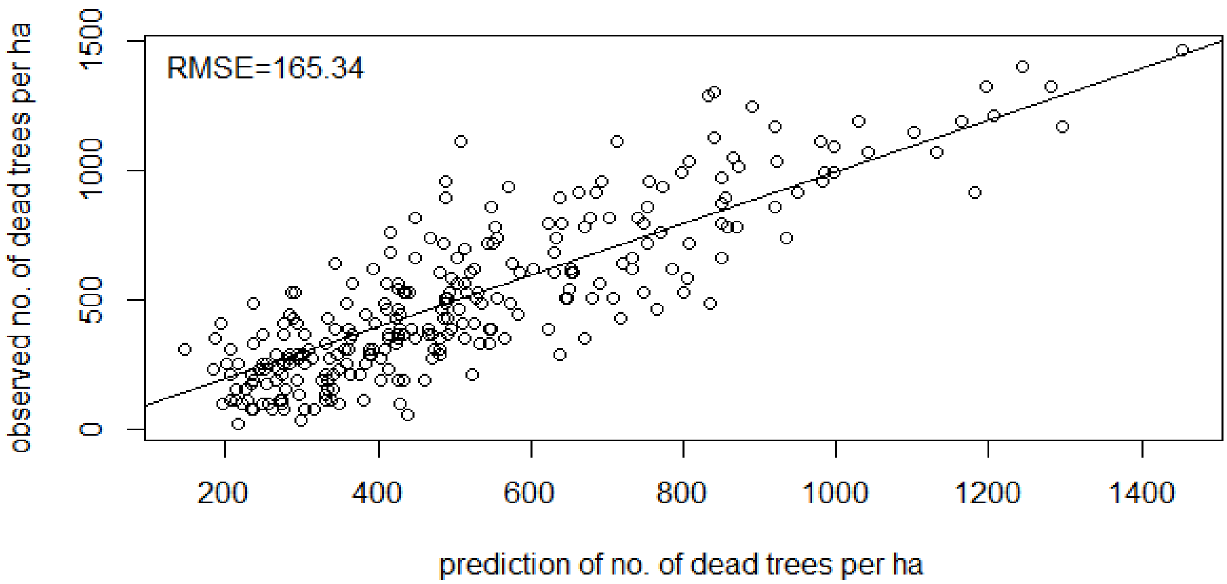

Figure 3.13. Prediction and observed of no. of dead trees per ha with Random Forest

The third tree-based method was Boosting, where 1,000 trees were produced sequentially and combined to create a single predictive model. Based on the cross-validation of the model, the lowest MSE rate could be achieved by setting the value of shrinkage parameter to 0.0216 (Appendix 14). The Boosting method in this study resulted a model with RMSE 166.39, which was slightly larger than Random Forest method (Figure 3.14). The high value of RMSE indicated that the model was not good enough to predict the number of dead trees through time.

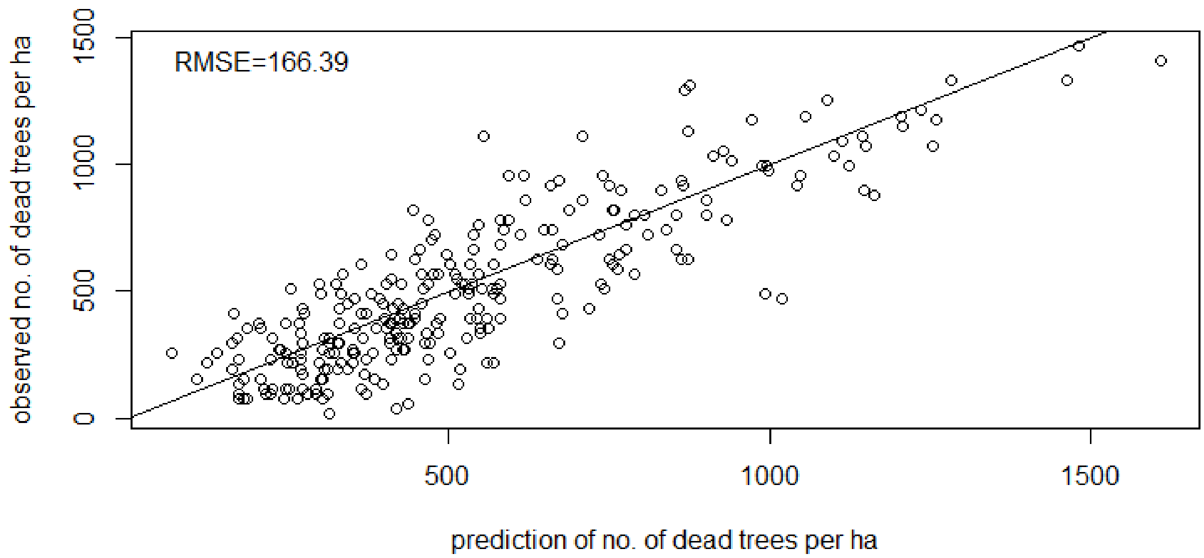

Figure 3.14. Prediction and observed of no. of dead trees per ha with Boosting

The relative influence plot of Boosting method showed that there were only two predictors variables in the dataset that had high relative influential values: measurement age and basal area per ha (Figure 3.15). These results suggest that the number of dead trees per ha was increasing with tree age and the basal area per ha. In this model, soil chemical, soil texture slope class, and soil physical were identified as the least influential variables in the model.

There were five different mixed-effect linear regression models that were developed to predict number of dead trees (Appendix 15). Model lmer3 was considered better compared to other models because it had the lowest RSME, which was 174.8 (Figure 3.16). However, the value of RMSE was still considered high. The high value of RMSE of the developed models indicated that the models were not good enough to predict the number of dead trees per ha through time.

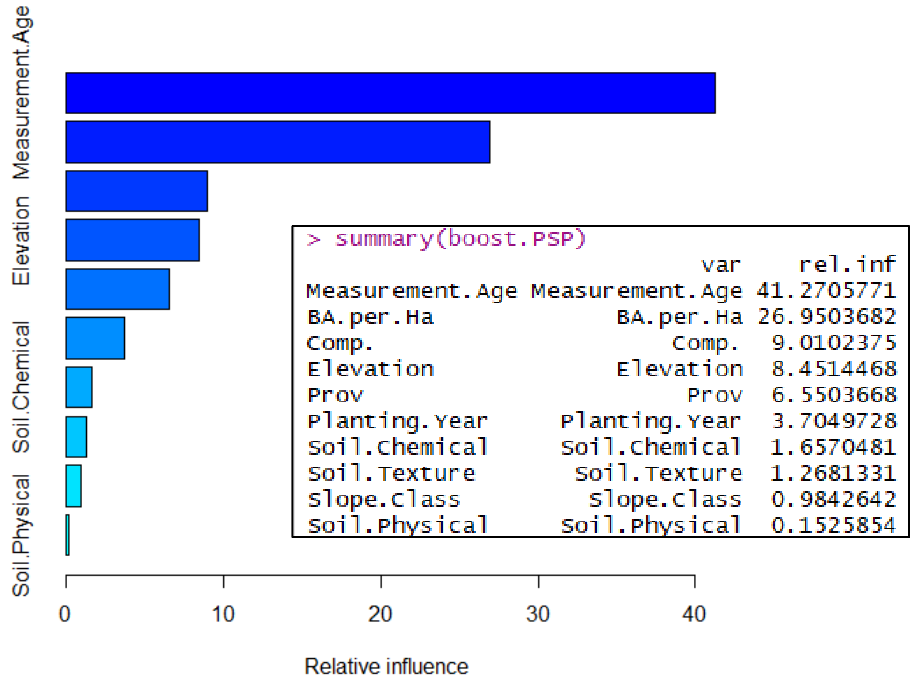

Figure 3.15. Relative influence plot of Boosting method in mortality model of *A. mangium* at stand level

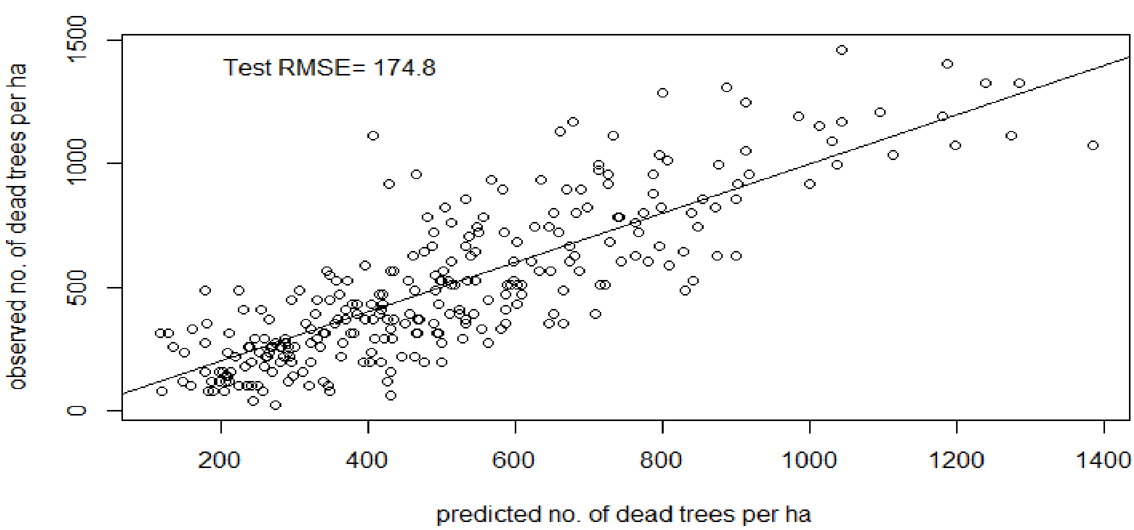

Figure 3.16. Prediction and observed of no. of dead trees per ha with mixed-effect linear model

Discussion

Growth, Productivity, and Mortality of A. mangium

Permanent sampling plot and simple random sampling plots are two type of samplings that are used commonly to assess the growth performance of the trees in forest plantation. Evaluation of growth performance based on measurement in permanent sampling plots that were established and measured consistently over time across the plantation provides valuable information on how the trees perform in the plantation. In this study, PT. FSS has successfully established 503 permanent sampling plots (PSP) from 2011 to 2017 to represent ± 25,000 ha of their *A. mangium* plantation. This method is considered to be more time consuming and needs more effort to number each tree in the plot observation than random sampling. Observers are also required to have more focus as they need to make sure to measure the same individual tree periodically. Simple random sampling plots is an alternative method to evaluate growth performance by taking random plot samples at different ages. This method has the assumption that all the plots have the same initial growth condition, which may make the evaluation less accurate. In addition, not all information on tree performance can be obtained through this sampling method, such as actual growth increment through time and new mortality through time.

Results from our data suggest that the growth performance of *A. mangium* was comparable to other studies. The average DBH and total height with planting space 3x3 m were slightly higher in plantations in South Sumatera (Eko B. Hardiyanto, Anshori, and Sulistyono 2004) and Riau (Nurwahyudi and Tarigan 2004) but lower in West Java with planting spacing of 3x2 m (Miyakuni et al., 2004). The differences on provenance used and the differences in soil quality might lead to different growth performance of *A. mangium* in these studies. Some studies reported that the growth performance and physical properties of provenance of *A. mangium* from Papua New Guinea was better than provenance from Queensland, Australia (Sahri et al., 1998; Tuomela et al., 1996). Another study reported that there were variations on growth and symbiotic performance on different provenance from Papua New Guinea (Vadez et al., 1995), while better growth performance was recorded on *A. mangium* that have type of soil that have better drainage (Nurudin et al., 2013b).

Survival rate of *A. mangium* in East Kalimantan based on our study was also comparable to other studies. In South Sumatera, the survival rate of *A. mangium* in the first year ranged from 73 to 95% (Eko B. Hardiyanto, Anshori, and Sulistyono 2004). Survival as high as 100% of *A. mangium* at 1.5-years-old was recorded at one permanent sampling plot in *A. mangium* plantation with planting space 3x2 m^2 in Riau (Mok et al., 2000). However, other studies from the same area showed that the average survival rate of *A. mangium* at one year was about 80% and kept decreasing to 51-31% after 3.5 years (Hardie et al., 2018b). At 6 year old, the best survival rate of *A. mangium* was recorded as high as 68%, in forest plantation in Sarawak, Malaysia (Jusoh et al., 2017).

The first year after planting is a critical time for the development of *A. mangium* in forest plantation, with widespread reports of high mortality in many forest plantations in humid tropical areas (Hardie et al., 2018b; Hardiyanto et al., 2004). Once the trees had established, the mortality rate become lower and started to increase again through time as the threat from causal agents were increasing through time. The permanent sampling plots used in this study did not include record of why trees were dead. Based on field observation in study area and literature review, there were some causal agents that might lead to mortality of *A. mangium* in the study area such as *Ceratocystis* wilt and root rot diseases.

In the first year, it is critical to maintain soil moisture during and soon after planting in the field (Hardie et al., 2018b). Providing the suitable planting hole was also important to make sure the roots of *A. mangium* establish well in the planting area. Seedlings of *A. mangium* become vulnerable to cricket and grasshopper attack from the day of planting until 3-4 weeks after planting. These insects become a problem when they feed on the stem, inhibiting water transport and possibly breaking the stem. During the chemical weeding at 3-months-old, it is important to make sure that herbicides do not drift onto the planted seedlings. There have been unpublished reports suggesting that such drifts can kill *A. mangium*. In addition, it is possible that some planting locations may not actually get planted with a seedling. Seedlings that were dead before three or four-months-old usually are difficult to trace during the measurement after year one, making it difficult to distinguish if the trees had been planted and died or had never been planted. From 6 to 12 months after planting, mortality due to rodent attack on *A. mangium* is commonly seen in some areas. This pest debarks the base of the stem of *A. mangium*, causing water transport inhibition from the root to the apical area. However, drift of herbicide, cricket, grasshopper and rodent attacks are uncommonly studied in forest plantation. The focus of attention in the first year after planting usually is on *Ceratocystis* wilt that is commonly observed from 6-months-old (Nasution et al., 2019; Tarigan et al., 2011a).

After seedling establishment in the first year, the threat of mortality agents usually decreases, resulting in the expected pattern of lower mortality rate in the second year. However, one causal agent that remains a problem is *Ceratocystis* wilt. Trees get more easily infected by this pathogen when there is a wound, especially during the rainy season (Brawner et al., 2015), which is why pruning and singling of *A. mangium* were stopped from maintenance practice in many forest operations (Chi et al., 2019; Nasution et al., 2019; Tarigan et al., 2011b). The annual mortality rate of *A. mangium* increased after the third year, likely due to increased prevalence of this pathogen. Beside the *Ceratocystis* wilt, there were also many reports on mortality of older *A. mangium* trees due to *Ganoderma* and *Phellinus* root rot diseases (Coetzee et al., 2011; Irianto et al., 2006). These fungi can spread to adjacent trees repeatedly through root contact in the soil or generatively through spores produced from fruiting bodies. Root rots can survive in the long term (at least 10 years) by infesting woody debris in the field (Chang, 1996). In addition, older *A. mangium* trees can be killed by tropical windstorms, especially in humid tropical area, although these events usually happens randomly (Hardie et al., 2018a).

Changes in Productivity and Mortality of A. mangium over time

The decreasing stand-level productivity of *A. mangium* at later planting years was not expected in this study because all the plots that were established were still in the first rotation. However, results from this study also show increasing mortality rates for a given age for later planting years. We suspect that the infection of tree diseases such as *Ceratocystis* wilt and root-rots to be main factors responsible for these trends. These pathogens can be spread from aerial spores or carried by insect vectors from one area to another (Hidayati et al., 2014; Roux and Wingfield, 2009).

The concern for increasing mortality of *A. mangium* through time emerged a few years ago, with recognition that *Ceratocystis* wilt and root rot problems were not easy to control at the operational scale (Eyles et al., 2008; Roux and Wingfield, 2009). The build-up inoculum of these diseases makes the incidence continue to increase over time (Lee, 2000). In severely affected areas, these two diseases can result in more than 50% mortality within 6 years after planting, decreasing potential yield of the trees at the stand level (Eyles et al., 2008; Hardie et al., 2018a; Lee, 2002; Mohammed et al., 2014; Roux and Wingfield, 2009). This report was comparable with the finding in our study where the survival rate of *A. mangium* 6 years after planting was lower than 50%.

There are not many simple options for decreasing the stand-level effects of these pathogens once they are present. Burning infected trees to reduce the inoculums of the pathogens in plantation area is not an option since many of the forest operations in Indonesia had implemented zero-burning policy in their concession area in order to achieve a sustainable management certification (Pasaribu and Supena, 2008; Prayoto et al., 2017). There is a management option to remove stumps and roots from planting area after harvesting to reduce the inoculum either manually or by using heavy machinery (Hagle and Shaw, 1991; Kile, 1993). However, this management practice is only feasible for high-value trees because this control method is costly. A more feasible option to reduce the inoculum is to delay replanting for the next rotation to allow infected stumps and wood debris to decay completely (Eyles et al., 2008). Setting the schedule for planting only in the wet season and harvesting only in the dry season resulted in lower root-rot incidence compared to planting continuously throughout the year (Irianto et al., 2006). Due to inability to do control measure to reduce the disease infection, many forest operations decided to change the species to *Eucalyptus pellita* or its hybrid that believed to have better resistance on *Ceratocystis* wilt and root rot diseases, even though the growth performance is not as good as *A. mangium* (Nambiar et al., 2018).

So far, genetic improvement of *A. mangium* species have not shown satisfying result on resistance to *Ceratocystis* wilt disease (Nasution et al., 2019). The lack of additive genetic variation in *A. mangium* species makes the development of resistant breeds more challenging (Brawner et al., 2015). However, *Acacia auriculiformis* shows higher levels of tolerance to *Ceratocystis manginecans*, and this tolerance may also be expressed in hybridization between *A. mangium* and *A. auriculiformis* (Trang et al., 2018). By integrating management practices between genetic improvement, disease control management, and soil management practice that conserves and enhances the productive capacity of soils, the productivity of *A. mangium* may be maintained. This strategic plan requires both new investments in and redirection of research and development, and stronger partnerships amongst all stakeholders committed to sustainability within the forest operation (Nambiar and Harwood, 2014).

Evaluation of Survival and Mortality Models of A. mangium

Tree mortality is a natural process that plays important roles in forest ecosystems and has a strong impact on stand productivity (Krisnawati, 2018). For many forest operations, this information needs to be accurately estimated to ensure the sustainability of wood supply that might be influenced by changing environment. Statistical learning, as used in this study, is a set of tools to make prediction from complex dataset (James et al., 2013). By dividing the dataset into training data and test data, we are be able to evaluate the performance of the model easily.

Tree-based methods that were used to build survival models of individual tree of *A. mangium* suggest that provenance selection needs to be considered, as this variable was found to be one of the important variables in tree classification method and boosting method. This suggests that some provenance might have better chance of survival compared to others, but this needs to be studied further both at experimental and operational scale to confirm this finding. Previous studies indicate that provenance can affect growth performance (Sahri et al., 1998; Tuomela et al., 1996; Vadez et al., 1995), but few studies provide strong evidence that provenance of *A. mangium* affects tree survival in the field as well. There was unexpected finding in this study, where we found that *A. mangium* tree with provenance Muting and P. Panjang that grow in the soil with less P and less K (soil chemical category D), have better chance to survive compared to those that grow in the soil with more P, K or both (soil chemical category A, B, or C). The inconsistent use of provenance across years might, which resulted in a lack of representation of each provenance across all possible planting conditions might lead to this finding. Thus, further study on provenance is still needed to confirm this finding.

The overall low misclassification rate (13.86% with RandomForest) and high false positive rate (66.33% with tree classification analysis) of survival models that were developed in this study indicated that the models were good to predict if an individual *A. mangium* tree would be alive in the following year but not good enough to predict if the tree is going to die. This might be caused by the lack of information in the dataset on causal agents that lead the mortality of the tree. Another possible reason is there may have been a lot of random mortality in the forest plantation, such as pest and disease or natural disturbance, that led to high variability on tree mortality. The high variation on number of dead trees per ha, which was also shown by high value of test RMSE in mixed-effect linear model (174.76 was the lowest), indicate that the random mortality event in the plantation is likely to happen or that the mortality patterns are not strongly associated to any particular factor. The prediction might be improved when we exclude the random mortality event in the dataset (Amateis et al., 1997; Diéguez-Aranda et al., 2005; Woollons, 1998).

Conclusion

In this study, we found that the productivity and mortality rate of *A. mangium* in forest plantation in East Kalimantan, Borneo, Indonesia, are comparable to other studies in humid tropical area. The trend of decreasing productivity and increasing mortality rate on permanent sampling plots that were established at different year were not expected in this study since all the plots were still in the first rotation. Tree diseases that can be spread from one to another were suspected to be one of the triggers of these trends. To maintain the productivity of *A. mangium*, integrated management practice based on research and scientific studies is needed. Research in forest plantation need to be strengthened and supported as it has important role to give clear information regarding recommendation practice to maintain sustainability of forest product in the long term.

The overall low misclassification rate and high false positive rate of survival models that were developed in this study indicated that the models were good to predict if an individual *A. mangium* tree would be alive in the following year but not good enough to predict if the tree is going to die. The high variation on number of dead trees per ha though time can also be seen in the study where the test RMSE in the mortality models that were developed were still high. The prediction might be improved when we focus the survival model only on certain mortality agent or exclude the random mortality event in the dataset. As one of important variables in the model, provenance need to be studied further to get better genetic material of *A. mangium* that have better survival chance in forest plantation system.

Chapter 4: Bark Beetles (Scolytinae: Coleoptera) and Sap-feeding Beetles (Nitidulidae: Coleoptera) Associated with *Acacia mangium* Willd. Infected by Ophiostomatoid Fungi in East Kalimantan, Borneo, Indonesia

Introduction

Acacia mangium is one of the main commodities in forest plantations in Indonesia. The tree species, native to Australia and eastern Indonesia, is well known for its ability to grow fast in a wide range of soil condition (Kamis Awang and Taylor, 1993; National Research Council, 1983). The suitability of its wood properties for the pulp and paper industry resulted in this tree species being grown extensively by many private forest operations in Sumatera and Kalimantan, Indonesia (Harwood and Nambiar, 2014). Despite its desirable properties, *A. mangium* was also known to be susceptible to many pests and diseases that can threaten the production of timber (Dell et al., 2012; Nambiar and Harwood, 2014; Wingfield et al., 2011).

Ceratocystis is one genus of ascomycotan fungi from the Ophiostomatoid fungi group that has caused much of mortality of *A. mangium* trees in forest plantations in Indonesia (Tarigan et al., 2011a). Symptoms of this tree disease include cankers, rapid wilting of foliage, and death of *A. mangium* trees. The symptoms are typically more common on young *A. mangium* trees that range from 6 to 12 months but can also be found on older trees. *Ceratocystis* spp. kills the woody tree species by invading parenchyma tissue and killing cambium and bark tissue, resulting in cankers (Lehtijärvi et al., 2018; Morris M. J.

et al., 1993). The cankers trigger the exudation of gum on the bark and discolored wood that turns to a uniform dark brown to dark blue color with age (Tarigan et al., 2011a). In forest plantations, *Ceratocystis* spp. invade the tree species through wounds, which may be caused by human activity, mammals, and natural damage (Harrington, 2007; Tarigan et al., 2011b). The pathogen can also be spread with rain or the help of insects attracted to the wound or sweet sap with fruity odor produced from the canker (Roux and Wingfield, 2009; Teviotdale and Harper, 1991). The sticky ascospores that were produced by this pathogen are easily attached to the exoskeleton of visiting insects (de Beer et al., 2014). The pathogen transmission can happen when the insects visit wounds on other susceptible trees. Bark beetle (Coleoptera: Scolytinae) and sap-feeding beetle (Coleoptera: Nitidulidae) are two group of insects that have been reported to have association with this ophiostomatoid fungi (Heath et al., 2009; van Wyk et al., 2004).

In North America, *Ceratocystis* spp. have been found to have association with *Ips* bark beetles (Yearian, 1966). Dutch elm disease (DED) in northern America, Canada and Europe was caused by ophiostomatoid fungi, also reported to be transmitted by *Scolytus* and *Hylurgopinus* bark beetles (Duhamel, 1967; Hubbes, 1999; Jacobi et al., 2013; Jin et al., 1996). Similar association was also found in Norway, where *Ips* bark beetles were found to be an insect vector of an ophiostomatoid fungi that causes wilt on Norway spruce (Brignolas et al., 1998; Krokene and Solheim, 1996). The association between bark beetles and ophiostomatoid fungi was also reported on pine species in South Africa (Zhou et al., 2001) and in Bhutan (van Wyk et al., 2004). Similarly, several sap-feeding beetle species had been reported to be vectors of *Ceratocystis* fungi on many tree species (Gilbert, 2011). Sap-feeding beetles from *Colopterus* genus have been found to carry spores of *Ceratocystis* species that cause wilt on oak species in Missouri, USA (Hayslett et al., 2008). In South Africa, ophiostomatoid spores were found on two sap-feeding beetle species in *Acacia mearnsii* plantation (Heath et al., 2009).

Despite the numerous records of bark beetle and sap-feeding beetle associations with ophiostomatoid fungi worldwide, information on bark beetle and sap-feeding beetle species in *A. mangium* plantations in East Kalimantan is still limited. There is no information on what bark beetle and sap-feeding beetle species occur on *A. mangium* trees that were infected by the ophiostomatoid fungi, and no information on how to monitor their presence in the plantations. We addressed these questions to improve understanding of the potential insect vectors that transmit *Ceratocystis* wilt disease and inform recommendations for plantation management to prevent spread of this disease in the plantation. Thus, two specific objectives were included in this study:

1. Compare and evaluate the diversity and abundance of bark beetle and sap-feeding beetles collected using two different methods in *A. mangium* plantations in East Kalimantan, Borneo, Indonesia, and
2. Review bark beetle and sap-feeding beetle species that can be potential insect vector of *Ceratocystis* wilt disease in *A. mangium* plantation in East Kalimantan, Borneo, Indonesia

Methods

Study Area

The study took place in the industrial forest plantation that was managed by PT. Fajar Surya Swadaya (PT. FSS) in East Kalimantan, Borneo, Indonesia that started to operate in 2011 (Figure 4.1). The total area of the forest plantation was 61,470 ha, which consisted of production area (50% of the total area), secondary forest, conservation area, rubber plantation as livelihood crops, and other land uses. The location of the study area was approximately 116^{o}03'29.20" E to 116^{o}32'01.20" E and 1^{o}10'47.12" S to 1^{o}25'00.83" S, which is near the equator. The climate in the study area was warm and humid year-round. Based on measurement from May to June 2019, the mean annual precipitation at study area was 1,913 mm, and the mean daily temperature was 31^{o}C, ranging from 25^{o}C to 35^{o}C. The elevation of the study area ranged from 10 to 286 m above sea level.

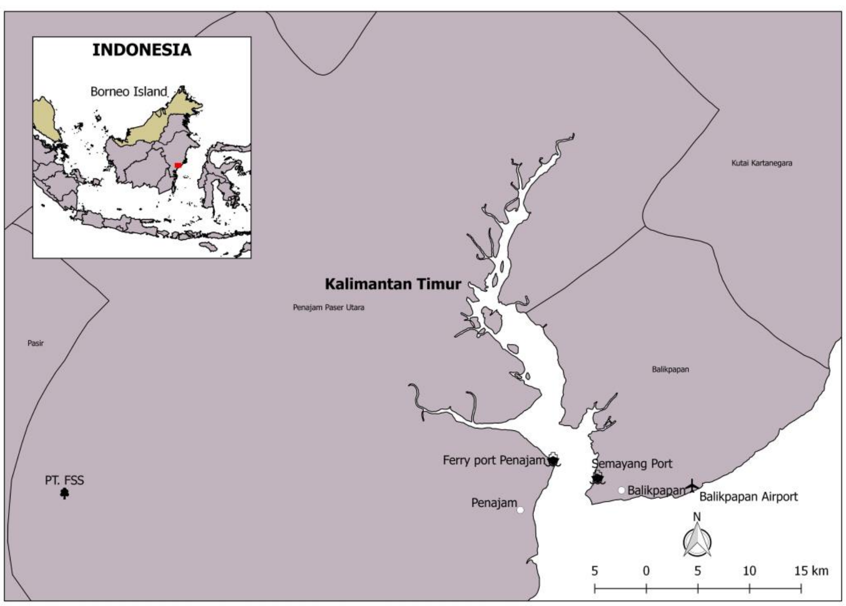

Figure 4.1. Location of study area in East Kalimantan, Borneo, Indonesia

A. mangium plantations within the production area are typically planted monoculturally using 3-months-old seedlings and managed at compartment level. The compartment size was about 25 ha and had irregular shape depending on soil contour. The planting density of *A. mangium* in this forest plantation was 2x3 m^2 and 2.5x3 m^2. The plantation was maintained with basic chemical fertilizer during planting and herbicide control of weeds applied 5 times for the whole planting rotation, the earliest was one month before planting and the latest was 12 months after planting. All *A. mangium* in this forest plantation were harvested at age 6 years, and the new rotation would begin after all the harvested logs were removed from the planting area. Permanent sampling plots (PSP) were established across the study area (Figure 4.2). Each plot was 512 m^2 and had a diamond shape and consisted of 80-120 trees.

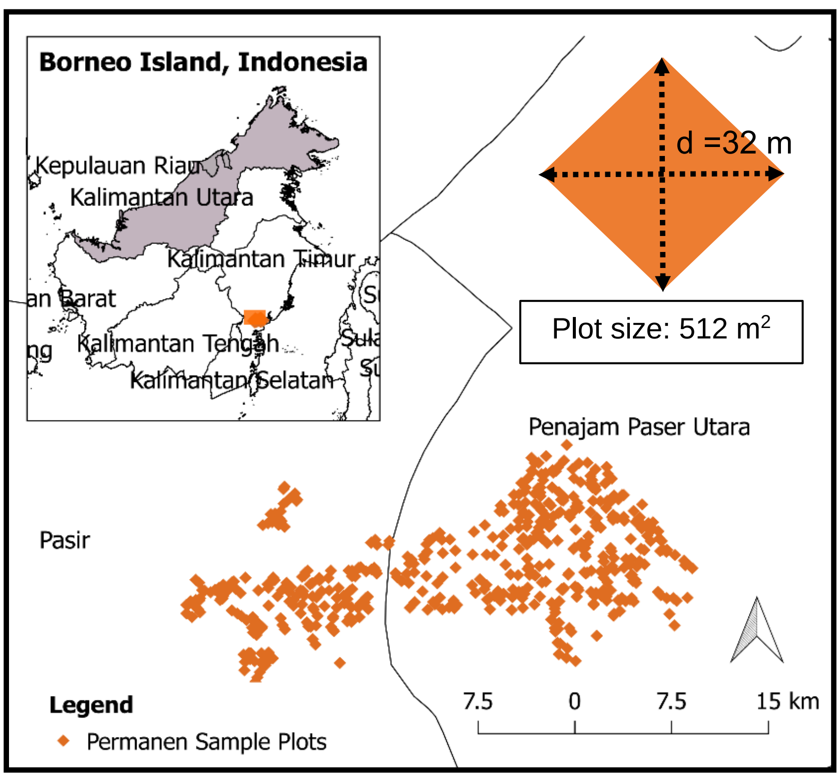

Figure 4.2. Distribution of permanent sampling plots (PSP) at PT. FSS

Insect Collection

There were two methods used to collect the bark beetles and sap-feeding beetles in *A. mangium* forest plantations. The first method of collection used funnel traps. Lindgren funnel traps modified with Allison collars were used to collect the flying beetles (Figure 4.3). Ethanol (96%) was used for bait and hung in the middle of the trap. Funnel traps were placed in each of nine sampling plots that were selected based on the highest tree mortality and the accessibility during the observation. In each plot, four funnel traps were placed at four different cardinal directions (north, south, east, and west), 6 meters away from the center point of the plot. Each trap was hung 1.5 meter above the ground and was checked after 3 days (Hanula et al., 2011; Powell, 2015). All the insects that were trapped in the funnel trap were collected and preserved in plastic tubes filled with EtOH 96% and labeled based on collection date, location, and plot number.

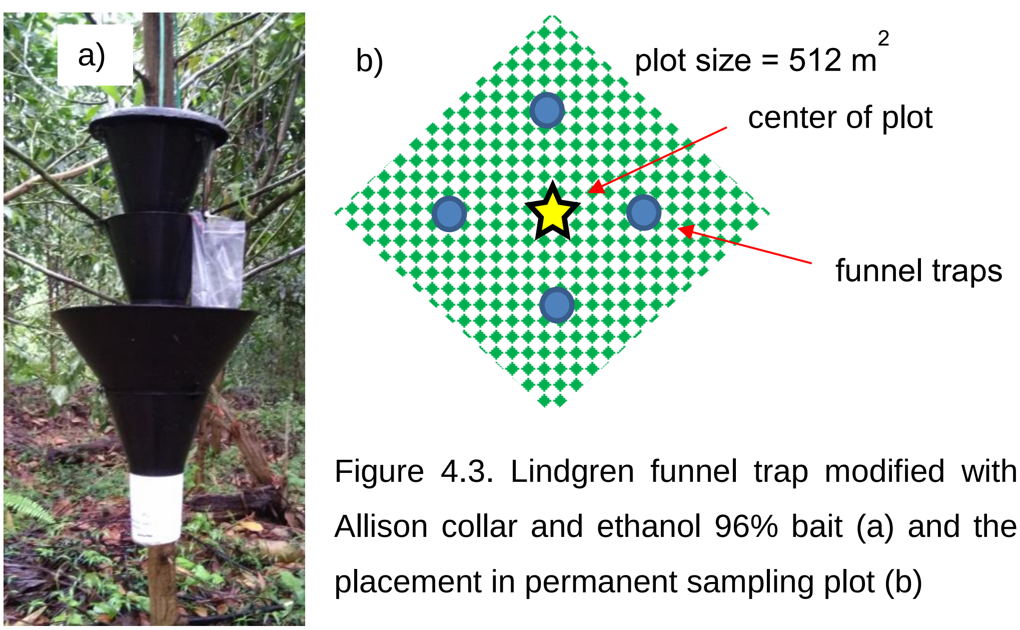

Figure 4.3. Lindgren funnel trap modified with Allison collar and ethanol 96% bait (a) and the placement in permanent sampling plot (b)

The second method of collection was by extracting logs of *A. mangium* from the field. Six 1-year-old *A. mangium* trees that were freshly infected by ophiostomatoid fungi were selected from different locations around permanent sampling plots that were established by the company for inventory data. Freshly infected trees produced sweet-smelling exudate of fermented gums at the infection site, which attracted beetles to feed on it (Figure 4.4). At this point in the infection, the leaves of *A. mangium* trees were starting to dry and wilt. Before the beetles were extracted from the logs, a 1-meter section of the infected area on the main stem was wrapped with newspaper and tied at both ends with plastic rope to prevent the beetles on the surface from escaping. The trees were then felled, and the section of the log was cut and wrapped again with transparent plastic before being brought to the lab. All the insects either on the surface or inside the logs were collected manually with a paint brush and preserved in plastic tubes filled with Ethanol 96%.

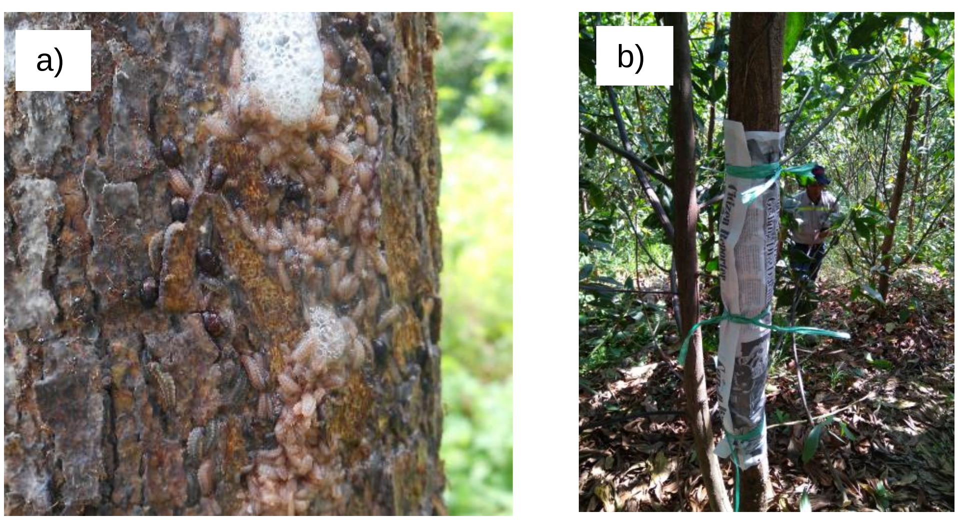

Figure 4.4. Freshly infected *A. mangium* tree by *Ceratocystis* wilt disease (a) and wrapping technique in log extraction method (b)

All arthropods that were collected from the funnel traps and log extraction were grouped into two categories: adult/imago or larvae/immature, and then identified into order level at Plant Health Lab, PT. FSS, based on identification keys of Triplehorn et al., (2005). Immature stage of insect collected in this study were excluded from the analysis because it is not possible to for us to identify them based on morphological characteristics (Stehr, 2005). Adult insects from order Coleoptera, were then continued to identify to family level using the same identification keys at Biological Control Lab, Dept. of Plant Protection, Bogor Agricultural University. Bark beetle family (Curculionidae, sub-family Scolytinae) were then continued to identify until morpho-species level based on identification keys of Bright (2014), while sap-feeding beetle family (Nitidulidae) were identified until morpho-species level based on identification keys of Gilbert (2011), Larson, (2013), and online guide (VanDyk, 2003). Each morpho-species of bark beetle and sap-feeding beetle was mounted and photographed using Leica microscope at Taxonomy Lab, Dept. of Plant Protection, Bogor Agricultural University. The identification of bark beetle species was then verified by Dr. Jiri Hulcr from University of Florida, while the identification of sap-feeding beetle species was verified by Dr. Andrew Cline from California Department of Food and Agriculture.

Species accumulation curves (SAC) were used to evaluate the sampling effort in assessing the diversity of bark beetles and sap feeding beetles on *A. mangium* trees in forest plantation in East Kalimantan, Borneo, Indonesia. The curves were formed from several adjusted asymptotic equations to describe the relationship between number of sampling effort and number of collected species. Asymptote was extrapolated as the maximum number of species that would be found with a hypothetical infinite sampling effort (Hortal et al., 2006; Lamas et al., 1991). We used R version 3.5.1 with r-package "vegan" to build the SAC in this study.

Results

There were 276 individuals of arthropods collected using the funnel trap method, in which 116 of them were Coleoptera (Appendix 1). On average, about 12 individuals were found in the 4 funnel traps that were set in each sampling plot. Aside from Coleoptera, Hymenoptera and Diptera were the two other most common insect orders that were trapped. From the log extraction method, there were 754 adults and 1,528 larvae of Coleoptera collected from the six different logs of *A. mangium* (Appendix 2). On average, there were about 125 adults and 254 larvae of Coleoptera found in a single *A. mangium* tree that was freshly infected by Ophiostomatoid fungi.

From all beetles collected using the two methods, 637 individuals were identified as bark beetles (order Coleoptera, subfamily Scolytinae), and 138 individuals were identified as sap-feeding beetles (order Coleoptera, family Nitidulidae). The most abundant bark beetle species was *Euwallacea fornicatus*. This bark beetle species represented 72% of all bark beetles that were collected using both methods (Figure 4.5). The next most abundant bark beetle was *Xyleborus bispinatus* (11%). For sap-feeding beetle family, the most abundance species was *Cryptarcha* sp.2. This species represented 31% of all sap-feeding beetles that were collected in the two methods (Figure 4.6). The other most abundant sap-feeding beetles included Carpophilinae sp.1 (16%) and *Cryptarcha* sp.1 (12%).

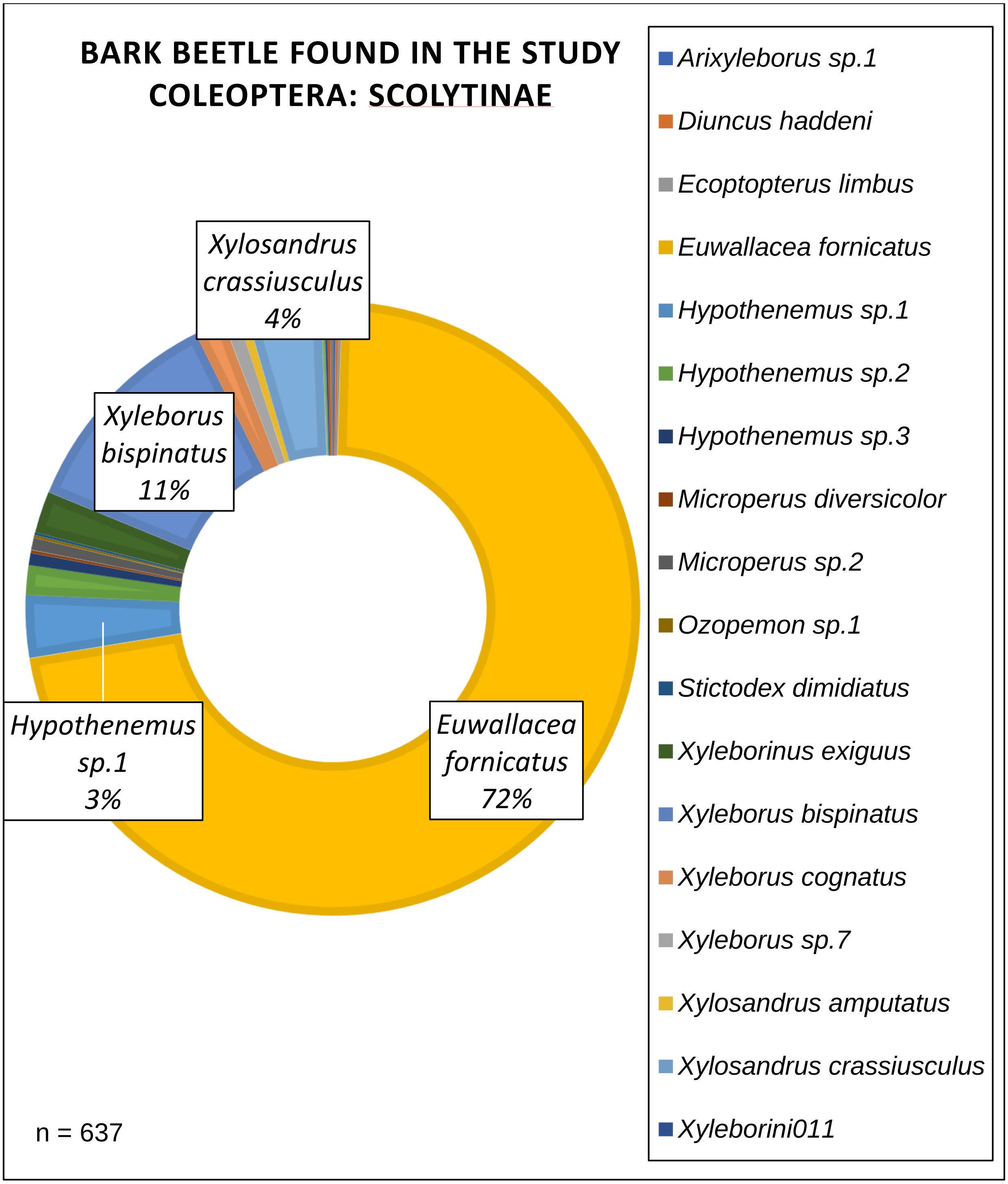

Figure 4.5. Relative abundance of bark beetles collected in the study

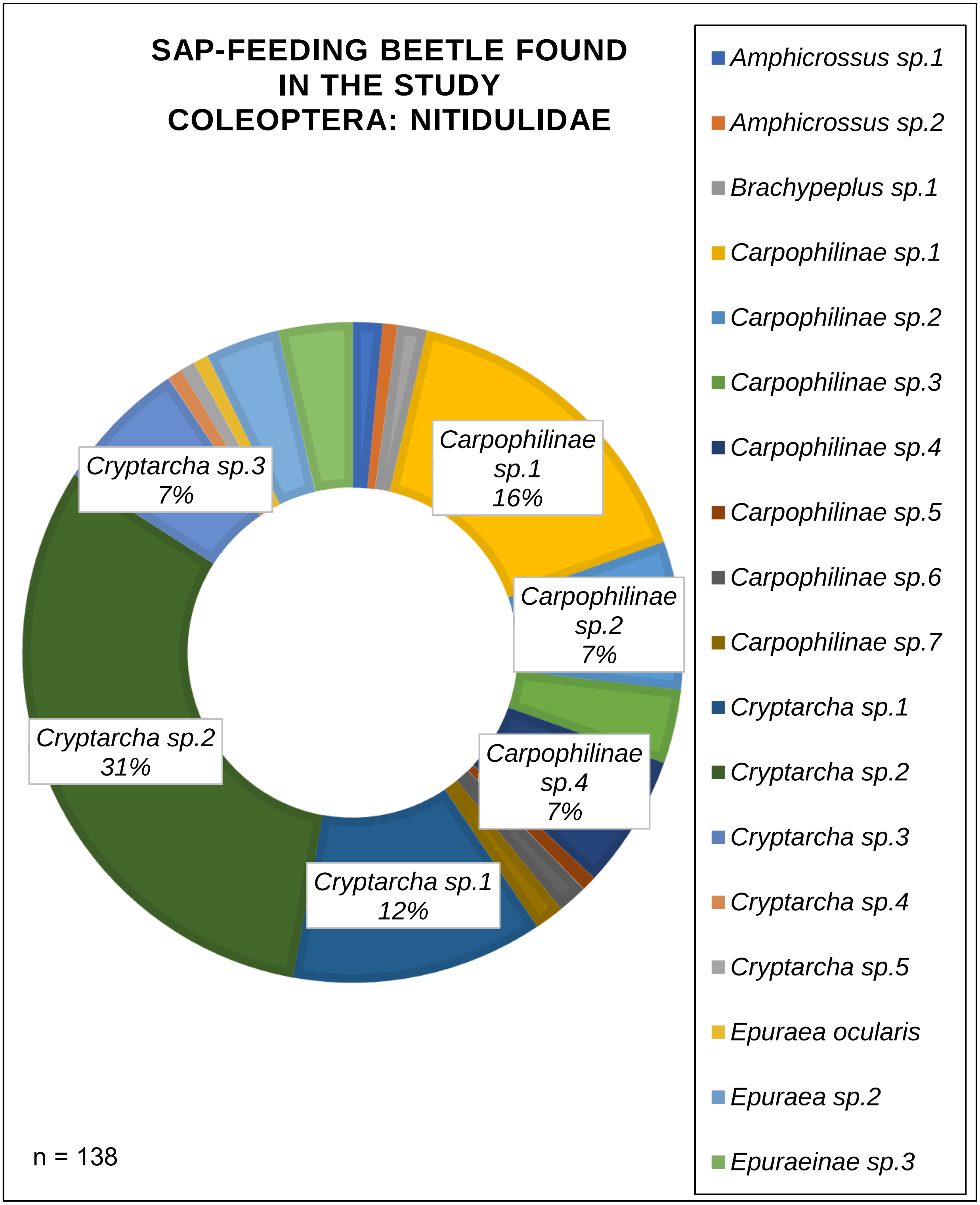

Figure 4.6. Relative abundance of sap-feeding beetles collected in the study

There were 11 species of bark beetle found in the log extraction method and 14 species of bark beetle found in the funnel trap method, and 4 species were found using both methods (Figure 4.7). *Euwallacea fornicatus* and *Xyleborus bispinatus*, the dominant bark beetle species collected in the study, were each only found using the log extraction method. These species represented 82% and 13% of 562 bark beetles collected in that method (Figure 4.9). For funnel trap method, the dominant bark beetle species was *Hypothenemus* sp.1 (24%), *Xylosandrus crassiusculus* (22%) and *Xyleborinus exiguus* (17%), each of which were also be found in log extraction method. For sap-feeding beetles, 18 species were found in log extraction method, and 2 species were found in funnel trap method, which could also be found in log extraction method (Figure 4.8). Among 136 individuals of sap-feeding beetles found in the log extraction method, *Cryptarcha* sp.2 (32%), Carpophilinae sp.1 (16%), and *Cryptarcha* sp.1 (13%) were found to be the dominant sap-feeding beetle species (Figure 4.10). In the funnel trap method, there were only 2 individuals of sap-feeding beetles that were captured, one was Carpophilinae sp.3, the other was Carpophilinae sp.4. These two sap-feeding beetle species were also found in the log extraction method.

The species accumulation curves (SAC) evaluated the sampling adequacy of bark beetle and sap-feeding beetle using log extraction in the study area. The SAC for bark beetles showed that the predicted asymptote of the curve would be achieved when the species richness was about 26, while the actual collected species were only 11 (Figure 4.11). For sap-feeding beetles, the predicted asymptote of the curve would be achieved when the species richness was about 32, while the actual collected species were only 18. Since the achieved species richness had not reach the asymptote, the models indicated that the sampling effort with log extraction method in this study was not enough.

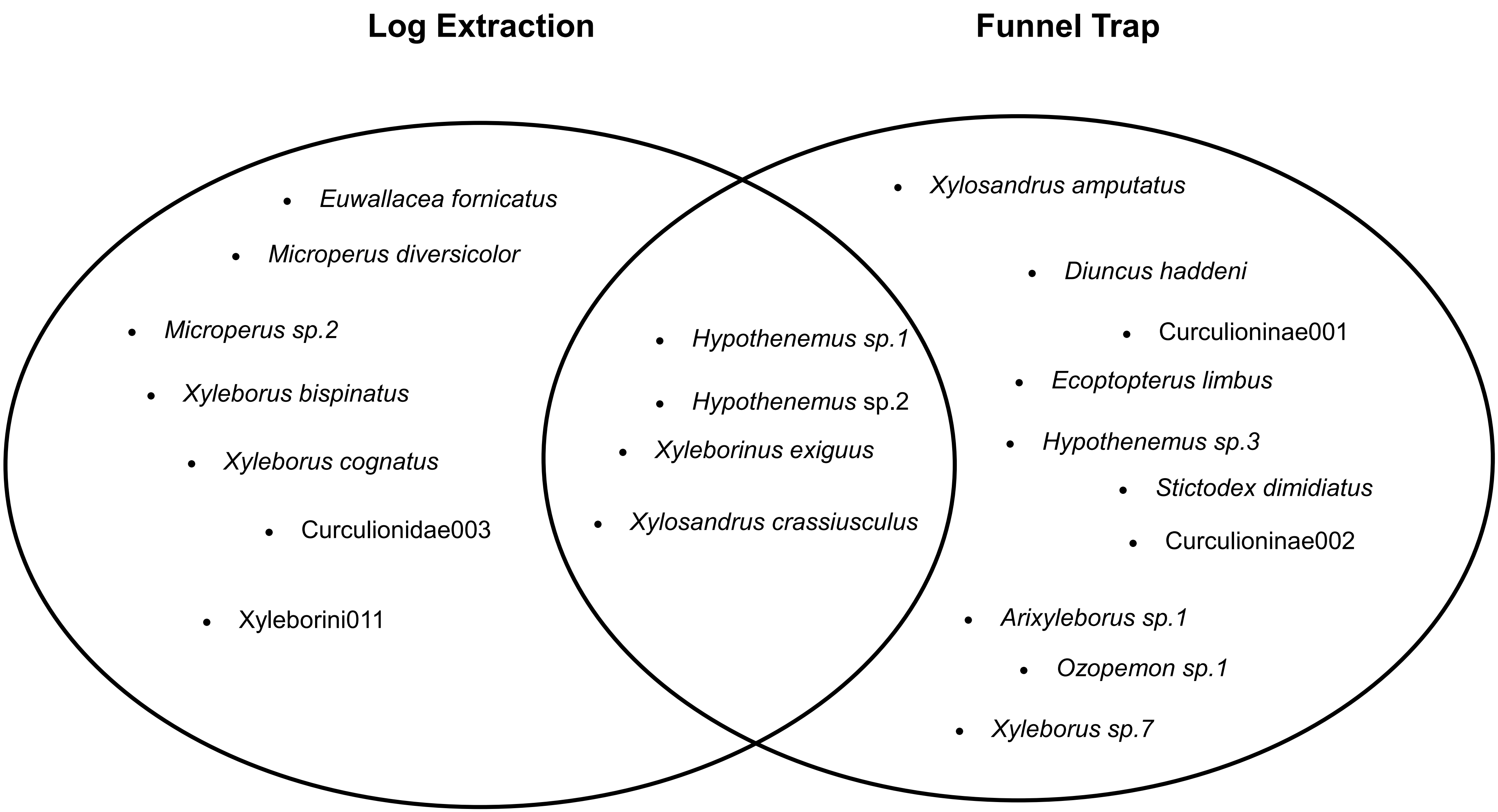

Figure 4.7. Diversity of bark beetle species collected from log extraction method and funnel trap method

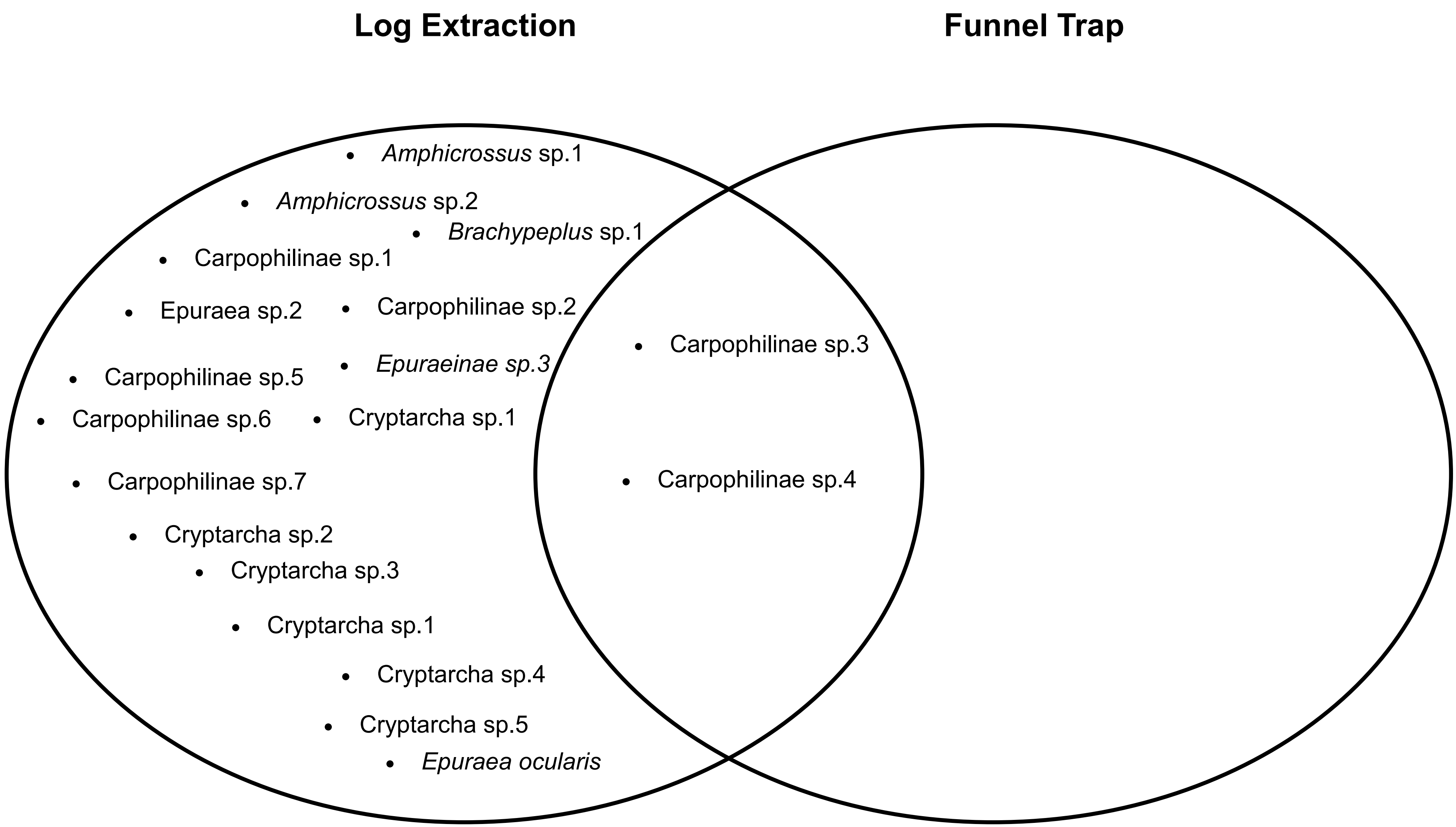

Figure 4.8. Diversity of sap-feeding beetle species collected from log extraction method and funnel trap method

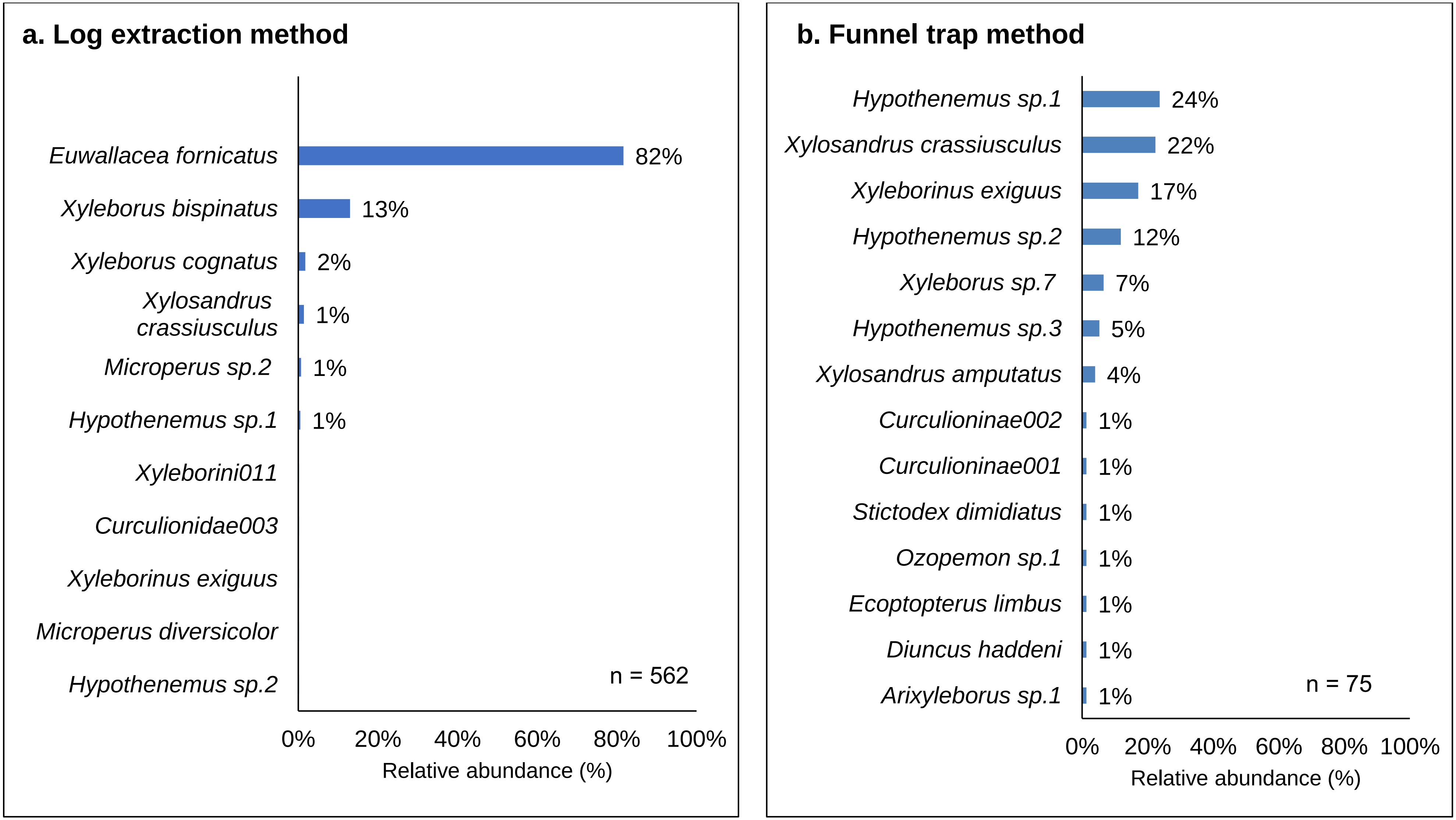

Figure 4.9. Relative abundance of bark beetle species (%) collected from log extraction method (a) and funnel trap method (b)

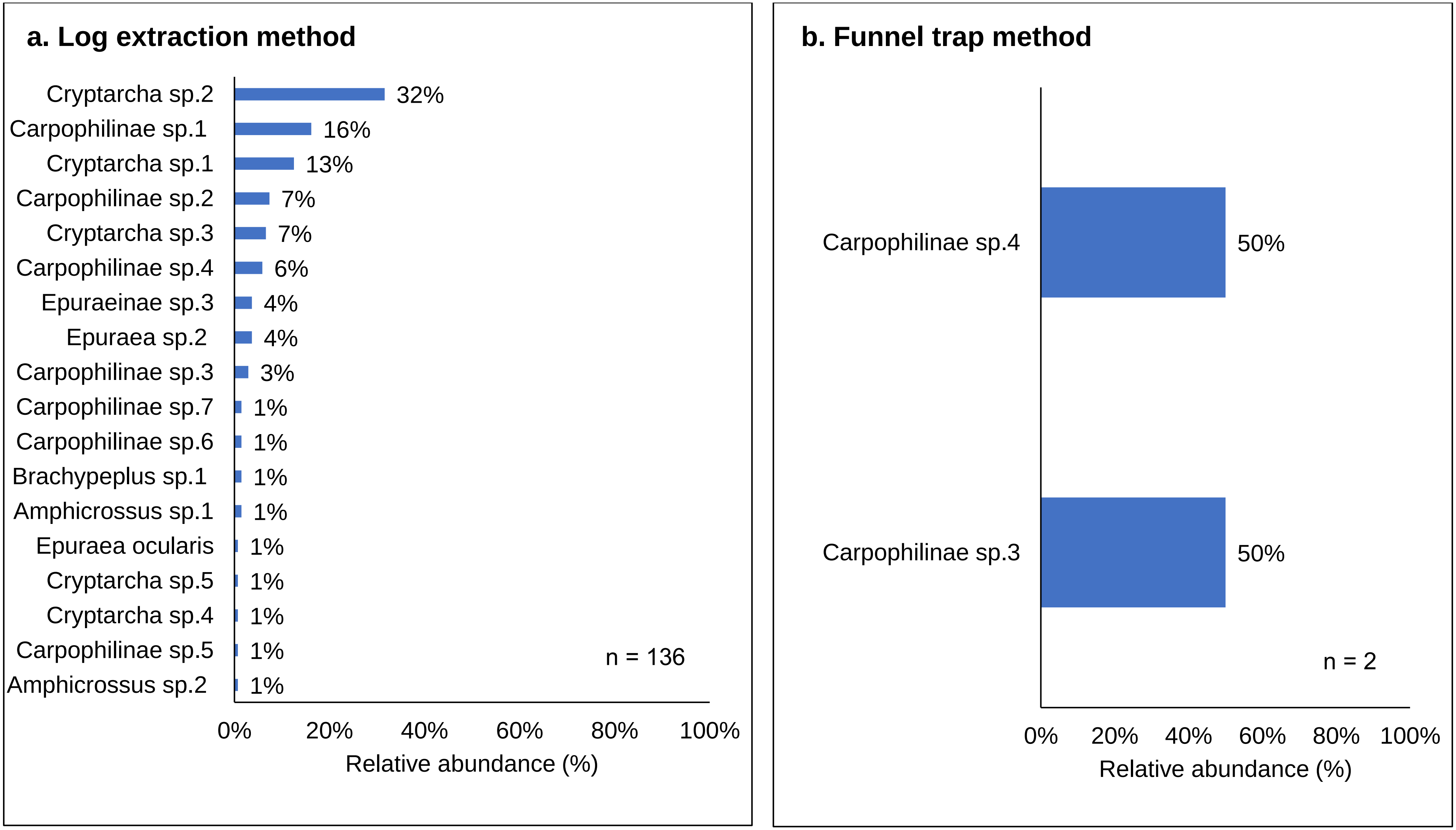

Figure 4.10. Relative abundance of sap-feeding beetle (%) collected from log extraction method (left) and funnel trap method (right)

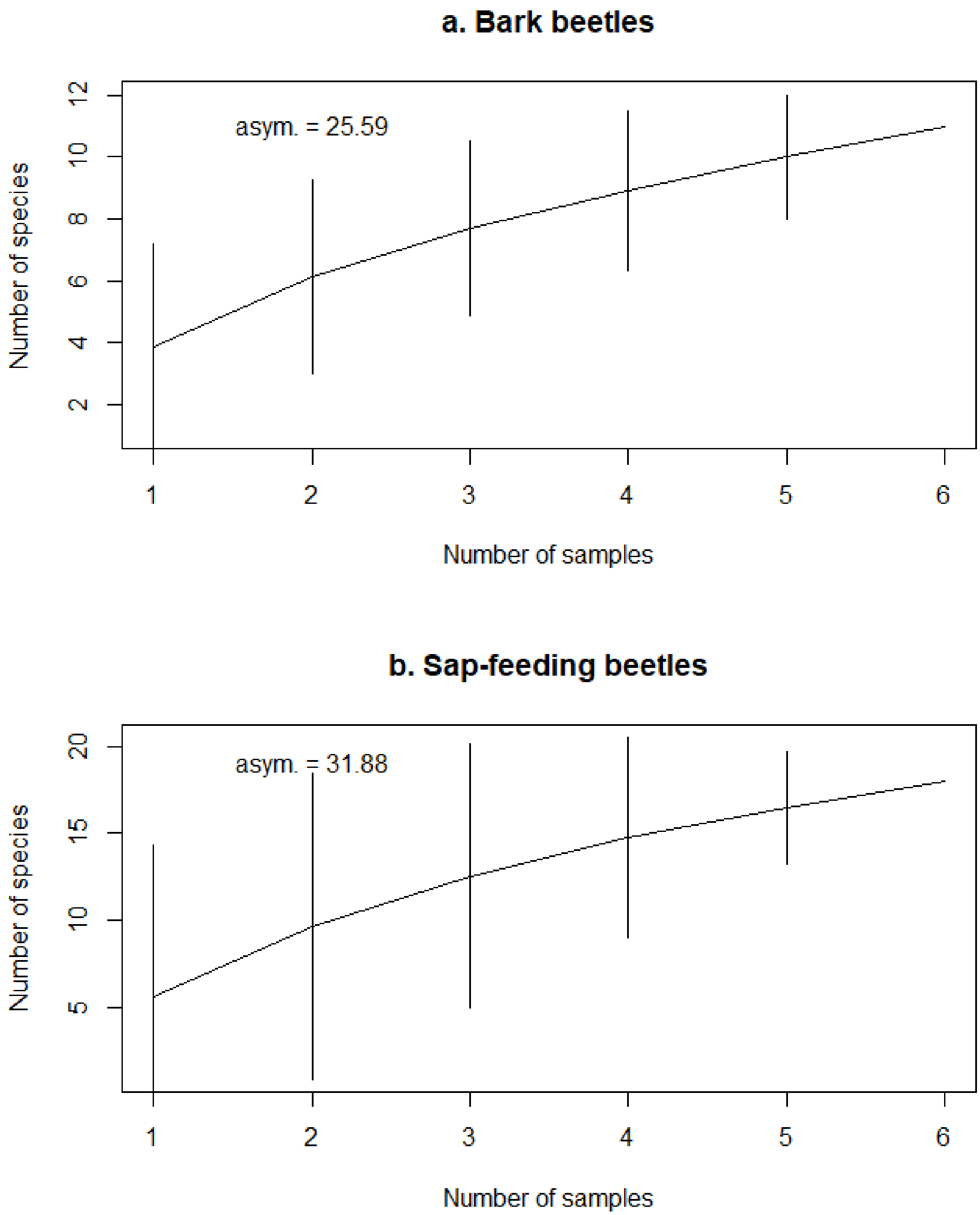

Figure 4.11. Species accumulation curves of bark beetle species (a) and sap-feeding beetle species (b)

Discussion

Sampling Comparison and Evaluation

Prior to this study, there has not been a report on bark beetles and sap-feeding beetles collected from canker wounds caused by ophiostomatoid fungi on *A. mangium* trees in East Kalimantan, Borneo, Indonesia. Thus, the information on bark beetles and sap-feeding beetle species that were collected in log extraction and funnel trap methods in the study is valuable for forest operations. Funnel trap and log extraction are two different methods that are used commonly to collect bark beetle and sap-feeding beetle in woodland or forest area. Funnel trap is used mostly to monitor the presence of certain insect species but can also be used as a mass trapping method to control insect populations when a large number of traps were used. The log extraction is used to assess the insect community in the log so the diversity and the abundance of the collected insect can be evaluated. In this study we used only a small number of funnel traps in each plot for monitoring and to compare with the log extraction method.

Bark beetle species and sap-feeding beetle species that were found in log extraction method could not be represented in funnel trap method. For example, *Euwallacea fornicatus* and *Xyleborus bispinatus*, the two most abundance bark beetle species in log extraction method, were not found in funnel trap method. This might be because the general bait or attractant that was used in the funnel trap method (EtOH 96%) is not suitable for these bark beetle species. Quercivorol and α-Copaene, which are available commercially, are two attractants that have been used to attract *Euwallacea fornicatus* (Byers et al., 2017; Carrillo et al., 2016; Dodge et al., 2017; Kendra et al., 2017), while

Xyleborus bispinatus has been found to be attracted by cubeb oil (Kendra et al., 2015). The same reason might apply to *Cryptarcha* sp.2, Carpophilinae sp.1, and *Cryptarcha* sp.1, the dominant sap-feeding beetle that could be found only in the log extraction method. *Cryptarcha* sp. and some Carpophilinae have been found to be attracted to whole wheat bread dough, fermenting brown sugar, cantaloupe, and banana (Williams et al., 1992).

In this study, we managed to collect only six samples using the log extraction method due to limitations of time in the field. However, from these 6 samples, we were able to collect a large number of bark beetles and sap-feeding beetles associated with Ophiostomatoid fungi and identify the beetle species dominating the beetle community. By increasing the number of samples until the species richness curve in species accumulation curve (SAC) reached the asymptote stage, we might have been able to achieve more representative values of the true species richness of bark beetle and sap-feeding beetle in *A. mangium* forest plantation. We could not perform SAC on bark beetle and sap-feeding beetle in funnel trap method, because the general bait used in this method was not good enough to attract all bark beetle and sap-feeding beetle species in the area, leaving a large number of NA value in observation. Some species of bark beetle and sap-feeding beetle could only be attracted by specific bait or attractant. This might be different with other bark beetle and sap-feeding beetle species. Thus, the funnel trap method does not appear to be suitable for assessing species richness of bark beetle and sap-feeding beetle.

Potential Insect Vector

Bark beetles and sap-feeding beetle species that were collected using the log extraction method have higher probability of association with Ophiostomatoid fungi pathogen than beetle species that were collected using the funnel trap method but not found in log extraction method. These beetles were attracted to the canker wound on the tree and colonized the tree. *Euwallacea fornicatus*, which is native to the area, was the dominant species in the logs. However, based on literature review, we have not found any report that *Euwallacea fornicatus* was found to have association with ophiostomatoid fungi. This bark beetle species has mostly been reported to be a vector of *Fusarium ambrosianum* on different tree species, causing Fusarium dieback disease (Table 4.1). The only *Euwallacea* species found to be a vector of ophiostomatoid fungi was *Euwallacea interjectus* on *Ficus carica* in Japan (Kajii et al., 2013). On the other hand, there has not been any report that *A. mangium* tree in forest plantation in Indonesia was killed by fusarium wilt disease. With the finding of large number of *Euwallacea fornicatus* invading *A. mangium* trees in the study area, there is possibility that this bark beetle species may be transmitting Fusarium dieback disease. Thus, there should be further study on this beetle on *A. mangium*.

From 18 morphospecies of nitidulid or sap-feeding beetle that were found in this study, we could identify only one to the species level, 9 to the genus level, and 8 others to the sub-family level. Lack of literature and other resources for identification for this large beetle family, especially in tropical area, made the identification difficult. In this study, genus *Cryptarcha* and subfamily Carpophilinae were found to be most abundant in the log extraction method. Both groups, as well as genus *Brachipeplus*, which was collected in a small number of samples using the log extraction method, have been found to have association with Ophiostomatoid fungi (Table 4.1). However, further study still needs to be done to confirm if these findings also applied in forest plantation in East Kalimantan, Borneo, Indonesia.

Table 4. 1. Bark beetle and sap-feeding beetle that had been reported associated with pathogenic fungi

Beetle Species	Genus	Sub-familiy	Host trees	Fungal Associate	References
a. Bark beetles					
Euwallacea fornicatus	*Euwallacea*	Scolytinae	*Robinia pseudoacacia, Camellia sinensis,* and other angiosperms	*Fusarium ambrosium, Sarocladium strictum, Graphium euwallaceae, Acremonium sp. Acremonium morum, Acremonium masseei, Elaphocordyceps sp.*	(Carrillo et al., 2016; Li et al., 2016; Mendel et al., 2012; O'Donnell et al., 2015)
Xyleborus bispinatus	*Xyleborus*	Scolytinae	*Persea* sp.	*Raffaelea arxii, Raffaelea lauricola*	(Ploetz et al., 2013)
b. Nitidulid beetles					
Brachipeplus depressus	*Brachipeplus*	Cillaeinae	*Acacia mearnsii*	*Ceratocystis albifundus, Ceratocystis oblonga*	(Heath et al., 2009)
Carpophilus bisignatus	*Carpophilus*	Carpophilinae	*Acacia mearnsii*	*Ceratocystis albifundus, Ceratocystis oblonga*	(Heath et al., 2009)
Carpophilus brachyopterus	*Carpophilus*	Carpophilinae	*Quercus* sp.	*Ceratocystis fagacearum*	(Skalbeck, 1976)
Carpophilus corticinus	*Carpophilus*	Carpophilinae	*Quercus* sp.	*Ceratocystis fagacearum*	(Skalbeck, 1976)
Carpophilus hemipterus	*Carpophilus*	Carpophilinae	*Saccharum* sp., *Acacia mearnsii*, *Quercus* sp., Stone fruit tree	*Ceratocystis albifundus, Ceratocystis oblonga, Ceratocystis fagacearum, Ceratocystis fimbriata*	(Skalbeck, 1976)
Carpophilus freemani	*Carpophilus*	Carpophilinae	Stone fruit tree	*Ceratocystis fimbriata*	(Tate, 1975)
Carpophilus lugubris	*Carpophilus*	Carpophilinae	*Platanus acerofolia*	*Ceratocystis platani*	(Skalbeck, 1976)
Carpophilus sayi	*Carpophilus*	Carpophilinae	*Quercus* sp.	*Ceratocystis fagacearum*	(Skalbeck, 1976)
Cryptarcha ampla	*Cryptarcha*	Cryptarchinae	*Quercus* sp.	*Ceratocystis fagacearum*	(Skalbeck, 1976)
Cryptarcha concinna	*Cryptarcha*	Cryptarchinae	*Quercus* sp.	*Ceratocystis fagacearum*	(Appel et al., 1990)

Conclusion

Our results suggest that the log extraction method is the best to assess the species richness and analyze insect community of bark beetle and sap-feeding beetle that might have association with pathogenic fungi in forest plantation area. However, since the potential species richness of the beetles based on SAC in this study has not been reached, there might be more bark beetle and sap-feeding beetle to be found in the study area with an increase in the number of samples in the log extraction method. Ethanol 96% that was used as bait in funnel trap was not effective to attract bark beetles and sap-feeding beetles that were found in log extraction. Some bark beetle species and sap-feeding beetle species require specific bait or attractant for beetle collection using funnel trap method.

For two most abundant bark beetle species found in the log extraction method, (*Euwallacea fornicatus* and *Xyleborus bispinatus*), there have not been reports of association with ophiostomatoid fungi. On the other hand, there were reports of the genus *Cryptarcha* and sub-family Carpophilinae of sap-feeding beetle that can be vector of ophiostomatoid fungi on some tree species. However, there is still no information on how likely sap-feeding beetles or bark beetle are transmitting their associated fungi in *A. mangium* plantation. Thus, further study needs to be done to confirm these findings.

Chapter 5: Summary, Synthesis, and Implications

In this study, we found that the productivity and mortality rate of *A. mangium* in forest plantation in East Kalimantan, Borneo, Indonesia, are comparable to other studies in humid tropical area. Integrated management practice based on research and scientific studies is needed to address the decreasing trend of productivity and increasing trend on mortality rate in the study area. Survival and mortality models that were developed in this study were insufficient for strength in prediction. Focusing the analysis on certain mortality agents or excluding irregular mortality events from the dataset could improve the prediction. Thus, it is important to improve inventory system by adding information on mortality agent contributing on mortality on *A. mangium* tree in the permanent sampling plots. The improved inventory system can be implemented either at experimental scale or plantation operational scale.

The funnel pan trap was not effective to attract bark beetles and sap-feeding beetles that have association with ophiostomatoid fungi due to unsuitability of bait or attractant used in the study area. The log extraction method identified some potential insect vectors of ophiostomatoid fungi and other pathogenic fungi on tree species. However, the potential species richness based on SAC using log extraction method have not been reached, because of the small number of samples that could be collected in this study. Further study needs to be done to confirm if bark beetle and sap-feeding beetle species found in this study can really transmit the disease on *A. mangium* in the forest plantation in East Kalimantan, Borneo, Indonesia. One of the options to achieve this objective is to run DNA detection or identification on ophiostomatoid fungi from bark beetles and sap-feeding beetles that were trapped using funnel trap in the area where the incidence of *Ceratocystis* wilt is high. However, suitable baits need to be used to attract specific bark beetle and sap-feeding beetle that had been identified as potential insect vectors of the diseases.

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Appendices

Appendix 1. List of Provenance in PT. Fajar Surya Swadaya

No.	Provenance	Location
1	Bupul	Papua New Guinea
2	C.Siro	Australia
3	Claudia River	far north Queensland, Australia
4	Deri-deri	Papua New Guinea
5	F1 Jogja	Jogjakarta, Indonesia
6	Gubam	Papua New Guinea
7	Jagebob	Papua New Guinea
8	Muting	Indonesia
9	Parung Panjang	Bogor, West Java, Indonesia
10	Queensland	Australia
11	Sebuhur	South Kalimantan
12	SM002	
13	SM014	
14	Subanjeriji	South Sumatra, Indonesia

Appendix 2. Soil Classification in PT. Fajar Surya Swadaya based on Soil Physical and Chemical

Symbol	Description
Low land, well drain soils, deep to moderately deep soils	
UPT.1	Fine particle size class (C, SiC, SC)
UPT.2	Fine loamy to fine silty particle size class (CL, SiCL, L, SCL)
UPT.3	Coarse loamy to coarse silty particle size class (SL, SiL, Si)
UPT.4	Very fine (hC) and fine (C-smektite) particle size class.
UPT.5	Sandy particle size class (S dan LS)
Low land, poorly drain soils, deep to moderately deep soils	
UPT.6c	Clayey, loamy, and silty particle size class.
UPT.6s	Sandy particle size class
Organic soils	
UPT.7a UPT.7e UPT.7i	Saprist Hemist Fibrist
Shallow soils	
UPT.8	-Any particle size class

Nutrient Status		K_2O (mg/100g)	
		Enough ($\geq$20)	Less (<20)
P_2O_5 (mg/100g)	Enough ($\geq$20)	A	B
	Less (<20)	C	D

Appendix 3. Result of ANOVA on average volume per hectare based on planting year based at different age of *A. mangium*

1. Age 1-year-old

```
                 Df Sum Sq Mean Sq F value Pr(>F)    
Planting.Year    6   3642   607.0   23.48 <2e-16 ***
Residuals      495  12797    25.9                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

2. Age 2-years-old

```
                 Df Sum Sq Mean Sq F value   Pr(>F)    
Planting.Year    5  10824  2164.8   12.53 2.93e-11 ***
Residuals      375  64805   172.8                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

3. Age 3-years-old

```
                 Df Sum Sq Mean Sq F value Pr(>F)    
Planting.Year    4  54322   13581    32.5 <2e-16 ***
Residuals      269 112416     418                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

4. Age 4-years-old

```
                 Df Sum Sq Mean Sq F value   Pr(>F)    
Planting.Year    3  61610   20537    28.2 1.38e-15 ***
Residuals      232 168928     728                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

5. Age 5-years-old

```
                Df Sum Sq Mean Sq F value Pr(>F)
Planting.Year    2  17397    8699   5.551 0.0046 **
Residuals      173 271076    1567
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

6. Age 6-years-old

```
              Df Sum Sq Mean Sq F value Pr(>F)
Planting.Year  1  15531   15531   6.205 0.0157 *
Residuals     56 140166    2503
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
1 observation deleted due to missingness
```

Appendix 4. Result of ANOVA on average number of trees per ha based on planting year based at different age of *A. mangium* using R-3.5.1

1. Age 0-year-old

```
               Df   Sum Sq Mean Sq F value   Pr(>F)    
Planting.Year   6  1776743  296124   9.807 3.17e-10 ***
Residuals     495 14947222   30196                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

2. Age 1-year-old

```
               Df   Sum Sq Mean Sq F value   Pr(>F)    
Planting.Year   6  2148631  358105   10.48 5.91e-11 ***
Residuals     495 16918557   34179                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

3. Age 2-years-old

```
               Df   Sum Sq Mean Sq F value   Pr(>F)    
Planting.Year   5  5588802 1117760   18.15 3.93e-16 ***
Residuals     375 23098336   61596                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

4. Age 3-years-old

```
               Df   Sum Sq Mean Sq F value Pr(>F)    
Planting.Year   4  8008718 2002179   42.65 <2e-16 ***
Residuals     269 12629409   46949                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

5. Age 4-years-old

```
               Df  Sum Sq Mean Sq F value Pr(>F)    
Planting.Year   3 6766004 2255335   53.28 <2e-16 ***
Residuals     232 9821018   42332                   
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

6. Age 5-years-old

```
               Df  Sum Sq Mean Sq F value   Pr(>F)    
Planting.Year   2  869610  434805   7.542 0.000724 ***
Residuals     173 9973276   57649                     
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

7. Age 6-years-old

```
              Df  Sum Sq Mean Sq F value Pr(>F)  
Planting.Year  1  298394  298394   5.254 0.0257 *
Residuals     56 3180379   56792                 
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
1 observation deleted due to missingness
```

Appendix 5. Result of ANOVA on average number of dead trees per ha based on planting year based at different age of *A. mangium* using R-3.5.1

1. Age 1-year-old

```
               Df   Sum Sq Mean Sq F value Pr(>F)  
Planting.Year   6   367018   61170   2.671 0.0147 *
Residuals     495 11338100   22905                 
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

2. Age 2-years-old

```
               Df   Sum Sq Mean Sq F value Pr(>F)    
Planting.Year   5  5984289 1196858   24.43 <2e-16 ***
Residuals     375 18372939   48995                   
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

3. Age 3-years-old

```
               Df   Sum Sq Mean Sq F value Pr(>F)    
Planting.Year   4 10604752 2651188   50.98 <2e-16 ***
Residuals     269 13990629   52010                   
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

4. Age 4-years-old

```
               Df   Sum Sq Mean Sq F value Pr(>F)    
Planting.Year   3  6498966 2166322   39.38 <2e-16 ***
Residuals     232 12761110   55005                   
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

5. Age 5-years-old

```
                 Df    Sum Sq Mean Sq F value   Pr(>F)   
Planting.Year     2    992043  496021   6.787 0.00145 **
Residuals       173 12644353   73089                     
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

6. Age 6-years-old

```
                Df  Sum Sq Mean Sq F value  Pr(>F)   
Planting.Year  1  403228  403228   7.255 0.00931 **
Residuals      56 3112561   55581                   
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

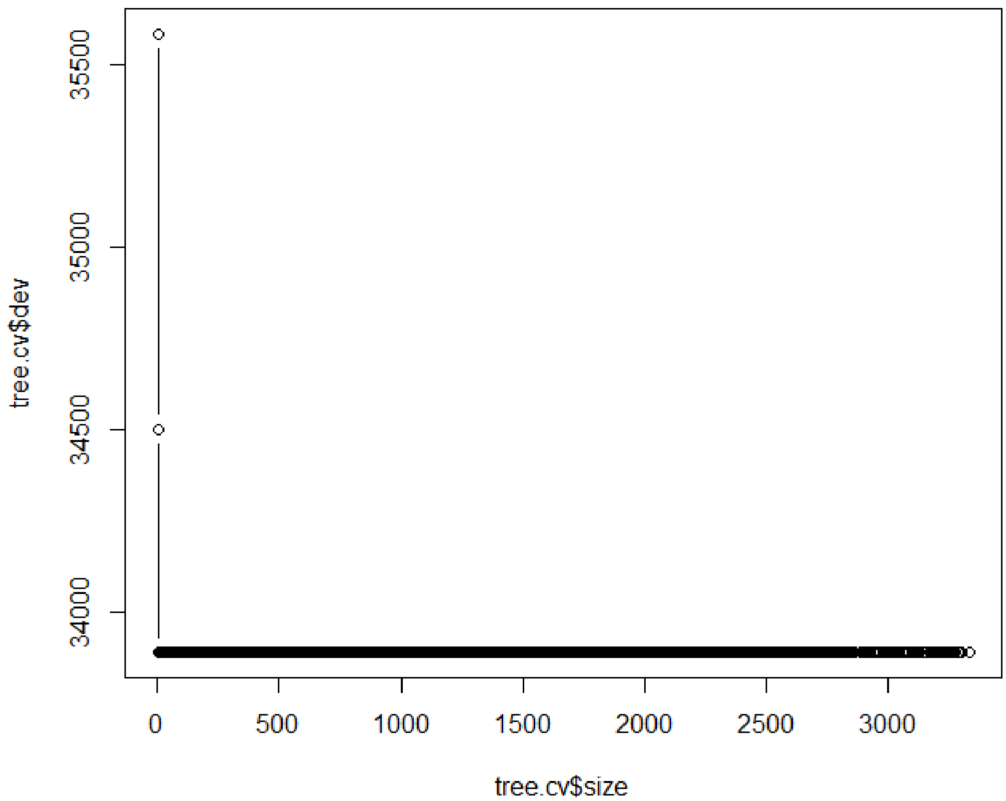
Appendix 6. Result of Pearson's correlation analysis (r) among response variable and predictor variables in the dataset for survival model of *A. mangium* at individual level

	Status Next Year	Diameter cm	Height m	Volume m^3	TPH	BA per Ha	Volume per Ha	No. of Dead Tree in plot	No. of Dead Tree per Ha	Measurement Age	Rounded Age	Prov.	Soil Texture	Soil Physical	Soil Chemical	Elevation	Slope Class	Planting Year	Comp.	PSP
Status Next Year	1.00	0.04	0.02	0.03	0.05	-0.03	-0.03	-0.06	-0.06	-0.05	-0.05	-0.09	0.01	-0.01	0.03	0.10	0.06	-0.15	0.01	-0.14
Diameter cm		1.00	0.91	0.91	-0.43	0.74	0.74	-0.30	-0.30	0.75	0.75	-0.09	0.03	-0.02	0.05	0.17	0.11	-0.29	-0.07	-0.29
Height m			1.00	0.85	-0.45	0.86	0.87	-0.35	-0.35	0.89	0.89	-0.14	0.03	-0.03	0.04	0.23	0.14	-0.39	-0.12	-0.38
Volume m^3				1.00	-0.41	0.66	0.71	-0.22	-0.22	0.71	0.71	-0.11	0.03	-0.02	0.05	0.19	0.11	-0.29	-0.04	-0.30
TPH					1.00	-0.25	-0.33	-0.12	-0.12	-0.49	-0.49	-0.11	-0.03	0.02	0.01	0.01	-0.05	0.20	0.17	0.19
BA per Ha						1.00	0.98	-0.46	-0.46	0.91	0.91	-0.20	0.02	-0.03	0.07	0.28	0.15	-0.39	-0.05	-0.39
Volume per Ha							1.00	-0.39	-0.39	0.94	0.94	-0.20	0.03	-0.03	0.07	0.29	0.16	-0.41	-0.06	-0.41
No. of Dead Tree in plot								1.00	1.00	-0.35	-0.36	0.18	-0.03	0.01	0.00	-0.21	-0.11	0.34	0.08	0.31
No. of Dead Tree per Ha									1.00	-0.35	-0.36	0.18	-0.03	0.01	0.00	-0.21	-0.11	0.34	0.08	0.31
Measurement Age										1.00	1.00	-0.19	0.04	-0.03	0.08	0.27	0.14	-0.44	-0.09	-0.44
Rounded Age											1.00	-0.19	0.04	-0.02	0.07	0.27	0.14	-0.44	-0.09	-0.45
Prov.												1.00	0.00	0.06	-0.06	-0.40	-0.08	0.38	-0.26	0.47
Soil Texture													1.00	0.83	-0.03	0.04	-0.01	-0.08	0.06	-0.10
Soil Physical														1.00	-0.02	-0.03	-0.06	0.08	0.13	0.05
Soil Chemical															1.00	0.22	0.06	-0.12	0.17	-0.17
Elevation																1.00	0.28	-0.51	-0.05	-0.51
Slope Class																	1.00	-0.25	-0.07	-0.25
Planting Year																		1.00	0.29	0.94
Comp.																			1.00	0.10
PSP																				1.00

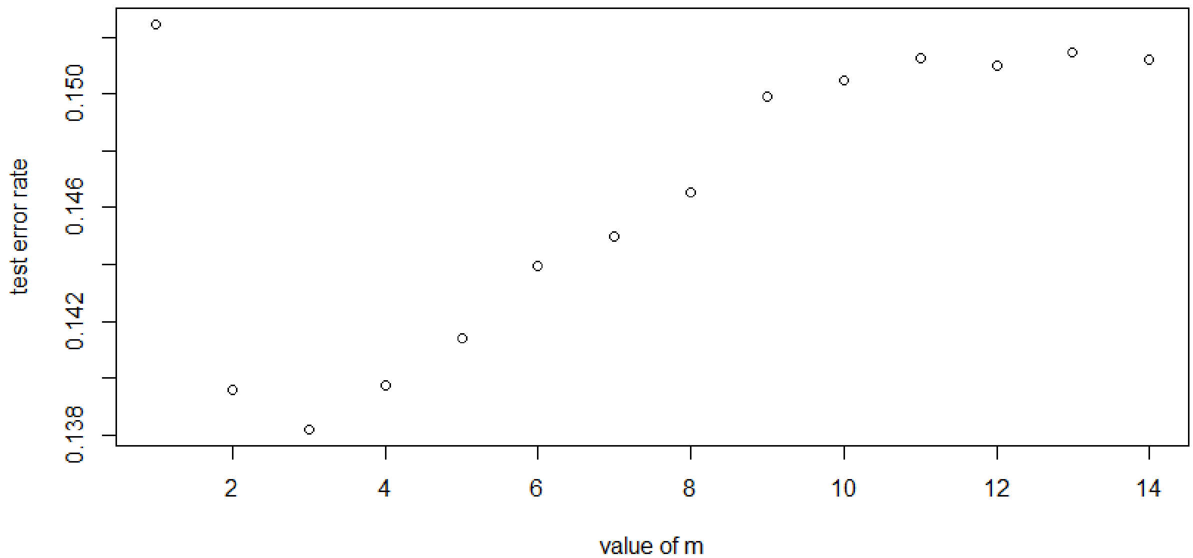
Appendix 7. Result of variance inflation factors (VIF) on several variables in the dataset using R v. 3.5.1

```
> vif(glm(Note.Next.Year ~ Height.m + Diameter.cm + Volume.m3, data = PSP, family = binomial))
   Height.m Diameter.cm    Volume.m3
   6.024008    9.188508    5.750273
>
>
> vif(glm(Note.Next.Year ~ Height.m + Volume.m3, data = PSP, family = binomial))
 Height.m Volume.m3
 3.729802  3.729802
>
>
> vif(glm(Note.Next.Year ~ BA.per.Ha + Volume.per.Ha + Measurement.Age, data = PSP, family = binomial))
      BA.per.Ha   Volume.per.Ha Measurement.Age
      20.419266       29.154537        7.696618
>
>
> vif(glm(Note.Next.Year ~ Volume.per.Ha + Measurement.Age, data = PSP, family = binomial))
  Volume.per.Ha Measurement.Age
       7.722153        7.722153
>
>
> vif(glm(Note.Next.Year ~ BA.per.Ha + Measurement.Age, data = PSP, family = binomial))
      BA.per.Ha Measurement.Age
       5.579482        5.579482
>
>
> vif(glm(Note.Next.Year ~ No.of.Dead.Tree.in.plot + No.of.Dead.Tree.per.Ha, data = PSP, family = binomial))
No.of.Dead.Tree.in.plot  No.of.Dead.Tree.per.Ha
               341662.5                341662.5
```

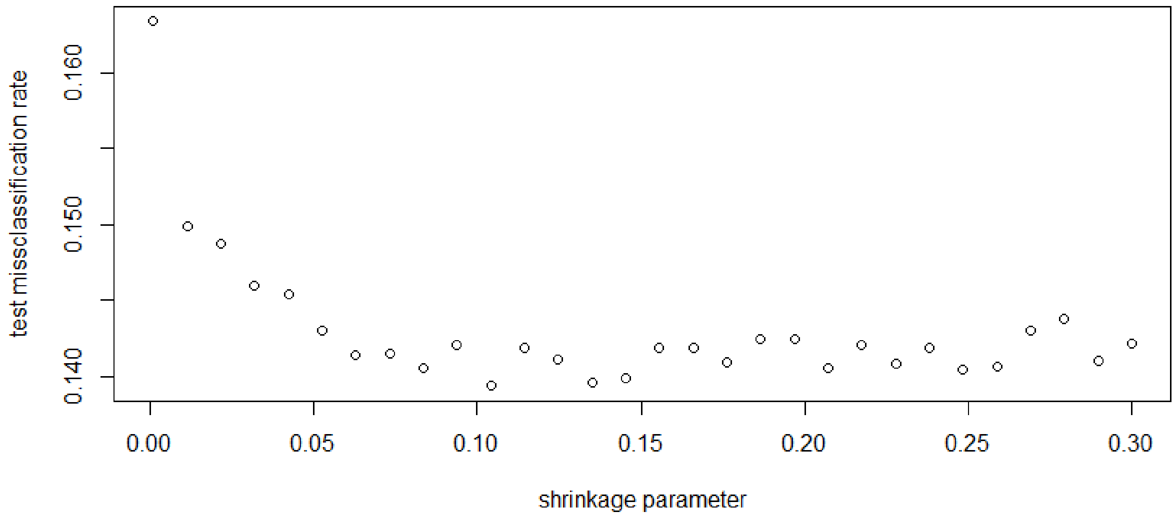
Appendix 8. Result of cross-validation in tree classification



Appendix 9. Result of cross-validation in Random Forests method in survival model



Appendix 10. Result of cross-validation in Boosting method



Appendix 11. Different mixed-effect logistic regression models to predict if an individual of *A. mangium* tree would survive in the following year

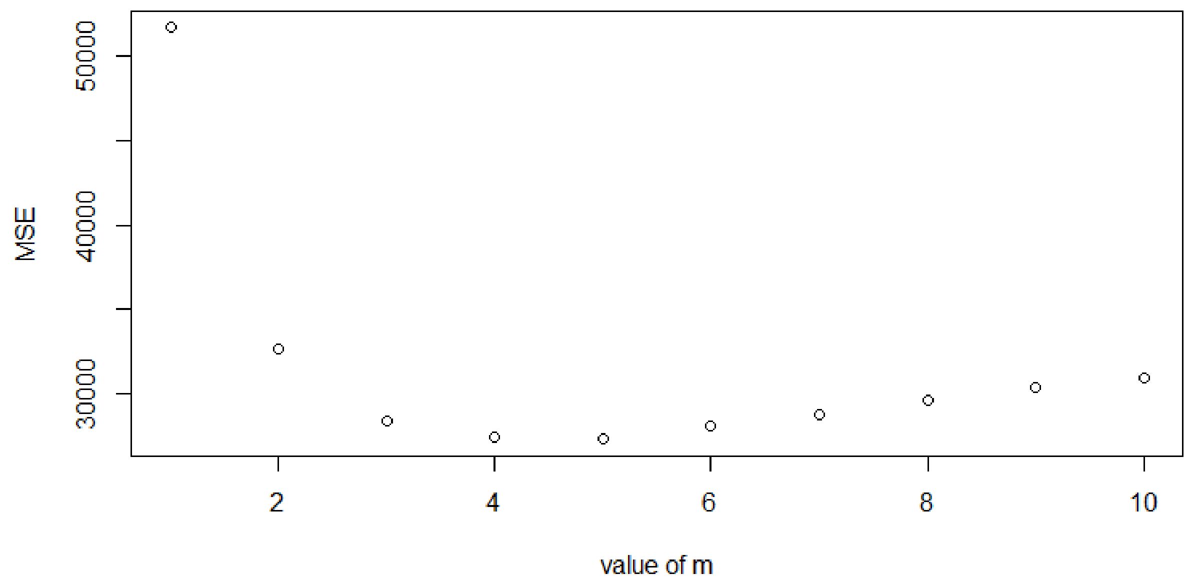
Model	Predictor Variables	AIC	Test Error Rate*	False Positive Rate	AUC of ROC
glmer1	Height.m+Volume.m3+BA.per.Ha+(Rounded.Age|Comp./PSP)	29096	14.56%	77.47%	0.796
glmer2	Height.m+Volume.m3+BA.per.Ha+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28969	14.54%	77.47%	0.796
glmer3	Height.m+Volume.m3+BA.per.Ha+(1|Prov)+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28952	14.55%	77.23%	0.796
glmer4	Height.m+Volume.m3+BA.per.Ha+(1|Slope.Class)+(1|Prov)+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28954	14.55%	77.24%	0.796
glmer5	Height.m+Volume.m3+BA.per.Ha+(1|Soil.Texture)+(1|Prov)+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28954	14.55%	77.24%	0.796
glmer6	Height.m+Volume.m3+BA.per.Ha+(1|Soil.Physical)+(1|Prov)+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28952	14.55%	77.30%	0.796
glmer7	Height.m+Volume.m3+BA.per.Ha+(1|Soil.Chemical)+(1|Prov)+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28954	14.55%	77.24%	0.796
glmer8	Height.m+Volume.m3+BA.per.Ha+Elevation+(1|Prov)+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28953	14.57%	77.30%	0.796
glmer9	Height.m+Volume.m3+BA.per.Ha+TPH+(1|Prov)+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28930	14.44%	76.82%	0.798
glmer10	Height.m+Volume.m3+BA.per.Ha+No.of.Dead.Tree.per.Ha+(1|Prov)+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28878	14.41%	76.47%	0.798
glmer11	Height.m+Volume.m3+BA.per.Ha+No.of.Dead.Tree.per.Ha+TPH+(1|Prov)+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28879	14.42%	76.53%	0.798
glmer12	Height.m*Volume.m3*BA.per.Ha*No.of.Dead.Tree.per.Ha+(1|Prov)+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28760	14.27%	76.35%	0.803
glmer13	Height.m*Volume.m3*BA.per.Ha+(1|Prov)+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28876	14.47%	76.64%	0.799
glmer14	Height.m+Volume.m3+BA.per.Ha+Height.m:Volume.m3+Height.m:BA.per.Ha+(1|Prov)+(1|Planting.Year)+(Rounded.Age|Comp./PSP)	28886	14.51%	76.64%	0.798

* At cut-off 50%

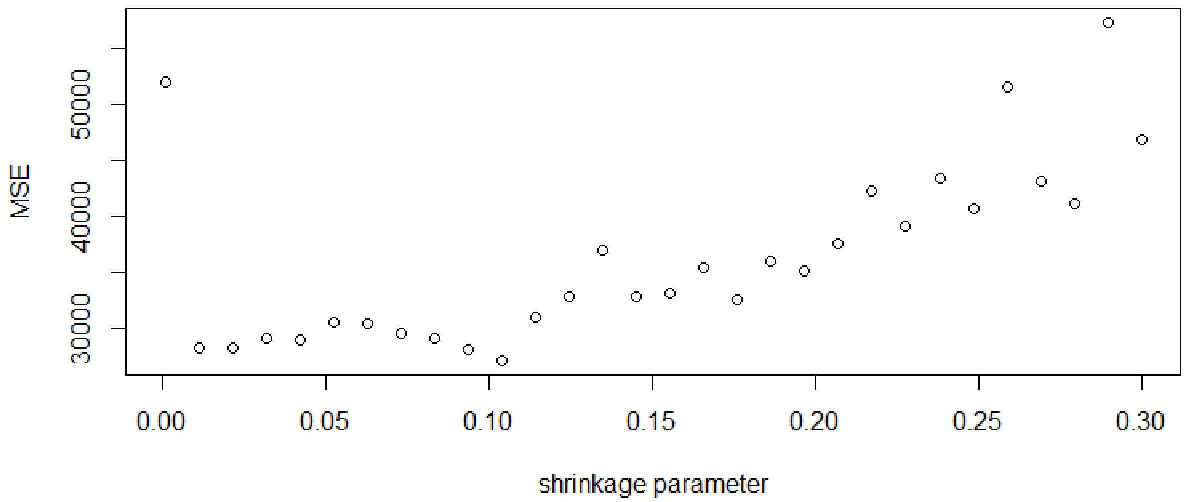
Appendix 12. The value of generalized variance inflation factors (GVIF) with dimension adjustment of predictor variables in mortality model of *A. mangium* at stand level

	GVIF	Df	GVIF^(1/(2*Df))
BA per Ha	3.55	1	1.88
Age (years)	3.44	1	1.85
Provenance	8713.72	13	1.42
Soil Texture	1617.87	3	3.43
Soil Physical	3656.69	3	3.93
Soil Chemical	2.08	3	1.13
Elevation	2.51	1	1.59
Slope Class	6.10	5	1.20
Planting Year	12489.34	6	2.19
Compartment	1380.16	9	1.49

Appendix 13. Result of cross-validation in Random Forests method in mortality model of *A. mangium* at stand level



Appendix 14. Result of cross-validation in Boosting method in mortality model of *A. mangium* at stand level



Appendix 15. Result of cross-validation in Boosting method in mortality model of *A. mangium* at stand level

Model	Response and Predictor Variables	AIC	Deviance	Test RMSE
lmer1	Rounded.Age+(1|Prov)+(1|Planting.Year)	15109.90	15099.90	228.42
lmer2	Rounded.Age+(1|Prov)+(1|Planting.Year)+(1|Comp.)	15064.20	15052.20	221.53
lmer3	BA.per.Ha+(1|Rounded.Age)+(1|Prov)+(1|Planting.Year)+(1|Comp.)	14694.80	14680.80	174.76
lmer4	BA.per.Ha+(1|Rounded.Age)+(1|Soil.Chemical)+(1|Planting.Year)+(1|Comp.)	14698.90	14684.90	175.29
lmer5	BA.per.Ha+Rounded.Age+(1|Prov)+(1|Planting.Year)+(1|Comp.)	14742.30	14728.30	185.63

Appendix 16. Arthropod collected from funnel trap method

No.	Comp.	Arthropods Order												
		Aran.	**Blat.**	**Chil.**	**Cole.**	**Coll.**	**Dipt.**	**Hemi.**	**Homo.**	**Hyme.**	**Isop.**	**Lepi.**	**Psoc.**	**Thys.**
1	MTC 274	1		1	4	1				8		2	1	
2	MTC 279	3			24	1	3			10			1	
3	MTC 289	2	1		16		1	1		10			1	1
4	MTC 292	1	2		14	2	3			7				
5	MTC 293	1			13		5		1	14	1		9	
6	MTD 030	3	1		8	9	5	1		7			2	
7	MTD 122	2			10	2	1			1		1	1	
8	MTD 126	2			8	5	1			6				
9	MTK 123				19	1	4			3			6	1
	Total	**15**	**4**	**1**	**116**	**21**	**23**	**3**	**1**	**66**	**1**	**3**	**21**	**2**

Note: Aran. = Araneae; Blat. = Blattodea; Chil. = Chilopoda; Cole. = Coleoptera; Dipt. = Diptera; Hemi. = Hemiptera; Homo. = Homoptera; Hyme. = Hymenoptera; Isop. = Isoptera; Lepi. = Lepidoptera; Psoc. = Psocoptera; Thys. = Thysanoptera

Appendix 17. Arthropod collected from log extraction trap method

No.	Compartment	Tree No.	Imago					Immature			
			Cole.	**Dipt.**	**Hemi.**	**Hyme.**	**Isop.**	**Blat.**	**Cole.**	**Dipt.**	**Isop.**
1	MTK 123	Tree 1	391		1		4		76		
2	MTK 123	Tree 2	167						88		
3	MTK 123	Tree 3	27		2	1			11		
4	MTC 293	Tree 4	43		1				43		
5	MTD 122	Tree 5	22								
6	MTC 289	Tree 6	104	1		1	1	1	1310	67	1
	Total		**754**	**1**	**4**	**2**	**5**	**1**	**1528**	**67**	**1**

Note: Blat. = Blattodea; Cole. = Coleoptera; Dipt. = Diptera; Hemi. = Hemiptera; Hyme. = Hymenoptera; Isop. = Isoptera

Appendix 18. List of bark beetle species (Curculionidae: Scolytinae) found in *A. mangium* forest plantation in East Kalimantan, Borneo, Indonesia

No.	Morphospecies code	Tribe	Genus	Fungus farming beetle / ambrosia beetle	Collection methods
1	*Arixyleborus* sp.1	Xyleborini	*Arixyleborus*	Yes	Funnel Trap
2	*Diuncus haddeni*	Xyleborini	*Diuncus*	Yes	Funnel Trap
3	*Eccoptopterus limbus*	Xyleborini	*Eccoptopterus*	Yes	Funnel Trap
4	*Euwallacea fornicatus*	Xyleborini	*Euwallacea*	Yes	Log Extraction
5	*Hypothenemus* sp.1	Cryphalini	*Hypothenemus*	No	Log Extraction, Log Extraction
6	*Hypothenemus* sp.2	Cryphalini	*Hypothenemus*	No	Log Extraction, Log Extraction
7	*Hypothenemus* sp.3	Cryphalini	*Hypothenemus*	No	Funnel Trap
8	*Microperus diversicolor*	Xyleborini	*Microperus*	Yes	Log Extraction
9	*Microperus* sp.2	Xyleborini	*Microperus*	Yes	Log Extraction
10	*Stictodex dimidiatus*	Xyleborini	*Stictodex*	Yes	Funnel Trap
11	*Xyleborinus exiguus*	Xyleborini	*Xyleborinus*	Yes	Log Extraction, Log Extraction
12	*Xyleborus bispinatus*	Xyleborini	*Xyleborus*	Yes	Log Extraction
13	*Xyleborus cognatus*	Xyleborini	*Xyleborus*	Yes	Log Extraction
14	*Xyleborus* sp.7	Xyleborini	*Xyleborus*	Yes	Funnel Trap
15	*Xylosandrus amputatus*	Xyleborini	*Xylosandrus*	Yes	Funnel Trap
16	*Xylosandrus crassiusculus*	Xyleborini	*Xylosandrus*	Yes	Log Extraction, Log Extraction
17	Xyleborini011	Xyleborini	-	Yes	Log Extraction

Appendix 19. List of sap-feeding beetle species (Nitidulidae) found in *A. mangium* forest plantation in East Kalimantan, Borneo, Indonesia

No.	Morphospecies code	Sub-family	Collection methods
1	*Amphicrossus* sp.1	Amphicrossinae	Log Extraction
2	*Amphicrossus* sp.2	Amphicrossinae	Log Extraction
3	*Brachypeplus* sp.1	Cillaeinae	Log Extraction
4	Carpophilinae sp.1	Carpophilinae	Log Extraction
5	Carpophilinae sp.2	Carpophilinae	Log Extraction
6	Carpophilinae sp.3	Carpophilinae	Log Extraction, Funnel Trap
7	Carpophilinae sp.4	Carpophilinae	Log Extraction, Funnel Trap
8	Carpophilinae sp.5	Carpophilinae	Log Extraction
9	Carpophilinae sp.6	Carpophilinae	Log Extraction
10	Carpophilinae sp.7	Carpophilinae	Log Extraction
11	*Cryptarcha* sp.1	Crypratchinae	Log Extraction
12	*Cryptarcha* sp.2	Crypratchinae	Log Extraction
13	*Cryptarcha* sp.3	Crypratchinae	Log Extraction
14	*Cryptarcha* sp.4	Crypratchinae	Log Extraction
15	*Cryptarcha* sp.5	Crypratchinae	Log Extraction
16	*Epuraea ocularis*	Epuraeinae	Log Extraction
17	*Epuraea* sp.2	Epuraeinae	Log Extraction
18	Epuraeinae sp.3	Epuraeinae	Log Extraction

Vita

Muhamad Nurhuda Nugraha was born October 25, 1989 in Lebak, Banten. Nugraha received his B.S. degree from Bogor Agricultural University, Indonesia, in September 2013. He majored in plant pest and disease and studied the diversity and parasitism of parasitoids on vegetable crops in Bogor for his bachelor thesis. During his study in Bogor, Nugraha experienced exchange programs at Kasetsart University, Thailand, and University of Goettingen, Germany, focusing on agriculture. After received his degree, Nugraha started his first professional work as research assistant in Jambi in a research project on arthropods diversity in oil palm plantation. Nugraha then continued to work as research officer at industrial forest plantation in Riau, focusing on pest and disease of *Acacia* spp. and *Eucalyptus* spp. In 2016, he moved the work to other industrial forest plantation in East Kalimantan as research supervisor. His main focus is on *Ceratocystis* wilt on *Acacia mangium* and other mortality agents in the forest plantation. In 2017, Nugraha received a fellowship from USAID-PRESTASI and CIFOR on forestry program and entered the School of Natural Resources MS program at the University of Missouri, Columbia.