



Faculty of Resource Science and Technology

**Ecological Study on Enrichment Planting of *Shorea macrophylla*
(de Vriese) P.S. Ashton for Restoration of Tropical Rainforest
Ecosystems in Sampadi Forest Reserve, Sarawak, Malaysia**

Mugunthan A/L Perumal

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(de Vriese) P.S. Ashton for Restoration of Tropical Rainforest
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Mugunthan A/L Perumal

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DECLARATION

I, Mugunthan A/L Perumal (15010105) from Faculty of Resource Science and Technology, hereby declare that this dissertation entitled, “Ecological Study on Enrichment Planting of *Shorea macrophylla* (de Vriese) P.S. Ashton for Restoration of Tropical Rainforest Ecosystems in Sampadi Forest Reserve, Sarawak, Malaysia” is based on my original work except for quotations and citations, which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

Implementation of effective soil conservation management and extensive information on the soil characteristics are indispensable in order to rehabilitate and manage degraded forest land in the humid tropics of Sarawak. Better understanding and implementation of nursery cultural regimes to improve seedling quality with high survival capability and optimal growth potential are one of the pivotal aspects of a successful forest restoration program. A preliminary assessment on the status of soil morphological and physicochemical properties after the enrichment planting of one potential Bornean tropical indigenous species, *Shorea macrophylla* (de Vriese) P.S. Ashton in comparison to an adjacent secondary forest was conducted at Sampadi Forest Reserve, Lundu, Sarawak. The present study was also carried out to evaluate the survivorship and growth performance of *S. macrophylla* as well as to evaluate the effect of enrichment planting on the soil fertility status with special reference to Soil Fertility Index (SFI) and Soil Evaluation Factor (SEF). A nursery experiment was set to determine the influences of inorganic and organic fertilisers on the morphological quality attributes of *S. macrophylla* seedlings in the Universiti Malaysia Sarawak nursery. *Shorea macrophylla* produced in the nursery and outplanted at Sampadi Forest Reserve was examined. The findings indicated that the soils in the study area consisted of mainly Grey-White podzolic soils which derived from a combination of sandstone, coarse-grained, humult ultisols, and sandy residual parent material. According to the Sarawak Soil Classification, the morphological properties resemble of Bako soil series as a dominant unit in association with Saratok series in which, corresponds to Typic Paleaquults of Soil Taxonomy by USDA-NRCS Classification. The general soil physicochemical properties indicated that the soils at reforestation sites and secondary forest were strongly acidic in nature with pH (H₂O) of less

than 5.5, poor in soil exchangeable bases and with low nutrient status. The soil texture was relatively of sandy clay loam to sandy clay and did not vary widely among the studied sites. Growth performance in terms of survivability; Mean Annual Increment of Height (MAIH) and Diameter (MAID) in SM96 (*S. macrophylla* planted in the year 1996) revealed the highest growth rate as compared to SM97, SM98, and SM99. Principal Component Analysis revealed three most significant components of the soil properties which explained 76.3% of the total variation. The first component score (PC1) was related to phosphorus content, soil acidity, and soil texture. PC2 inferred soil organic matter constituent and cation retention capacity, while PC3 related to available nutrient of the soils. Notwithstanding, a significant association was found between soil available phosphorus and *S. macrophylla*, indicating that soil phosphorus is a better indicator than SFI at surface soils. The findings also revealed that morphological quality attributes of *S. macrophylla* seedlings treated with organic jellyfish fertiliser (JF) were significantly higher ($P < 0.05$) than the seedlings treated with chemical fertiliser (CF) and controlled-instant release fertiliser (CIRF) at the end of nursery growing season. Older (9- and 24-month-old) *S. macrophylla* seedlings growth were morphologically different from younger (3- and 6-month-old) seedlings. Pooled mean survival rates overall declined from 61.7 to 44.6% after 12, 24, and 42 months of outplanting. The initial seedling age at the time of planting had significant effects on the subsequent growth performance and biomass production of seedlings. Seedling quality evaluation requires the integration of both morphological and physiological attributes of seedlings that provides a more effective appraisal of the fitness of seedlings to become established for field planting especially in the tropical forest rehabilitation area of Sarawak, Malaysia.

Keywords: Forest restoration, enrichment planting, *Shorea macrophylla* (de Vriese) P.S.

Ashton, soil fertility, Sarawak

Kajian Ekologi Tanaman Diperkaya dengan Shorea macrophylla (de Vriese) P.S. Ashton untuk Restorasi Ekosistem Hutan Hujan Tropika di Hutan Simpan Sampadi, Sarawak, Malaysia

ABSTRAK

Pelaksanaan pengurusan pemuliharaan tanah yang berkesan dan maklumat luas mengenai ciri-ciri tanah adalah penting untuk pemulihan tanah hutan yang terdegradasi di kawasan tropika Sarawak. Pemahaman dan pelaksanaan semaian yang baik bagi meningkatkan kualiti anak pokok dengan survival yang tinggi dan potensi pertumbuhan optimum adalah satu aspek penting dalam program restorasi hutan yang berjaya. Penilaian awal terhadap status sifat morfologi dan fizikokimia tanah selepas penanaman satu spesies asli tropika Borneo yang berpotensi, Shorea macrophylla (de Vriese) P.S. Ashton berbanding dengan hutan sekunder telah dijalankan di Hutan Simpan Sampadi, Lundu, Sarawak. Kajian ini dijalankan untuk menilai kadar survival dan prestasi tumbesaran S. macrophylla serta untuk menilai kesan penanaman terhadap status kesuburan tanah dengan rujukan khas Indeks Kesuburan Tanah (SFI) dan Penilaian Faktor Tanah (SEF). Satu eksperimen tapak semaian telah dijalankan untuk menentukan pengaruh baja bukan organik dan organik terhadap sifat morfologi anak pokok S. macrophylla yang dihasilkan di tapak semaian Universiti Malaysia Sarawak. Shorea macrophylla yang dihasilkan di tapak semaian dan yang ditanam di Hutan Simpan Sampadi telah dicerap. Hasil kajian menunjukkan tanah di kawasan kajian terdiri daripada tanah podzolik berwarna kelabu-putih dan kebanyakannya berasal dari kombinasi batu pasir, bijian kasar, 'humult' ultisols, dan bahan induk sisa berpasir. Mengikut Klasifikasi Tanah Sarawak, sifat morfologi menyerupai siri tanah Bako sebagai unit dominan yang bersekutu dengan siri tanah Saratok yang bersesuaian dengan Taksonomi Tanah 'Typic Paleaquults' oleh Klasifikasi USDA-NRCS. Ciri-ciri umum fizikokimia tanah

menunjukkan tanah di kedua-dua kawasan restorasi hutan dan hutan sekunder berasid dengan pH (H₂O) kurang daripada 5.5, pertukaran kation tanah yang kurang dan status nutrien yang rendah. Tekstur tanah terdiri daripada tanah liat berpasir kepada tanah liat dan tidak banyak berubah di antara tapak kajian. Prestasi tumbesaran dari segi kadar survival dan tumbesaran ketinggian tahunan (MAIH) dan diameter tahunan (MAID) di SM96 (S. macrophylla ditanam pada tahun 1996) menunjukkan kadar pertumbuhan tertinggi berbanding SM97, SM98, dan SM99. 'Principal Component Analysis (PCA)' telah mengelaskan ciri-ciri tanah kawasan kajian kepada tiga komponen utama dan menjelaskan 76.3% daripada jumlah variasi PCA tersebut. Hubungkait signifikan antara kandungan fosforus tanah dengan pokok S. macrophylla telah didapati dan menunjukkan fosforus tanah adalah petunjuk yang lebih baik daripada SFI pada permukaan tanah. Hasil kajian pada akhir tempoh semaian menunjukkan anak pokok S. macrophylla yang dirawat dengan baja organik obor-obor (JF) adalah lebih baik dan signifikan ($P < 0.05$) berbanding dengan baja kimia (CF) dan baja kimia terkawal (CIRF). Pertumbuhan anak pokok S. macrophylla yang lebih tua (9 dan 24 bulan) adalah berbeza secara morfologi daripada yang lebih muda (3 dan 6 bulan). Purata kadar survival menurun daripada 61.7 kepada 44.6% selepas 12, 24, dan 42 bulan penanaman. Umur awal anak pokok pada masa penanaman mempunyai kesan yang signifikan terhadap prestasi tumbesaran dan biojisim S. macrophylla. Penilaian kualiti anak pokok memerlukan integrasi kedua-dua sifat morfologi dan fisiologi agar dapat memberikan penilaian yang lebih berkesan terhadap kesesuaian anak pokok untuk ditanam terutamanya di kawasan pemulihan hutan hujan tropika di Sarawak, Malaysia.

Kata kunci: Restorasi hutan, tanaman diperkaya, Shorea macrophylla (de Vriese) P.S.

Ashton, kesuburan tanah, Sarawak

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LIST OF SYMBOLS

%	per cent
°C	degree Celsius
$\mu\text{S cm}^{-1}$	micro Siemens per centimetre
A horizon	surface soil (top soil) horizon
AB horizon	intermediate horizon between A and B horizon
Al Sat.	Al saturation
Avail. P	available phosphorus
B horizon	subsoil horizon
Base Sat.	base saturation
BD	bulk density
C/N	carbon to nitrogen ratio
CEC	cation exchange capacity
EC	electrical conductivity
ECEC	effective cation exchange capacity
Exch. Al^{3+}	exchangeable aluminium
Exch. Ca^{2+}	exchangeable cation of calcium
Exch. K^{+}	exchangeable cation of potassium
Exch. Mg^{2+}	exchangeable cation of magnesium
Exch. Na^{+}	exchangeable cation of sodium
H_2O	water
KCl	potassium chloride
MC	moisture content

ns	no significant differences
O horizon	organic matter horizon
OM	organic matter
pH	acidity or basicity
<i>P</i> value	probability value
r/ R^2	correlation coefficient
<i>s</i>	standard deviation
SUM	sum of exchangeable bases
T-C	total carbon
T-N	total nitrogen
$\bar{x}$	mean

LIST OF ABBREVIATIONS

AAS	Atomic Absorption Spectrophotometer
ANOVA	Analysis of Variance
cm	centimetre
$\text{cm cm}^{-1} \text{ day}^{-1}$	centimetre per centimetre per day
$\text{cm cm}^{-1} \text{ mo}^{-1}$	centimetre per centimetre per month
$\text{cm}^2 \text{ seedling}^{-1}$	square centimetre per seedling
$\text{cmol}_c \text{ kg}^{-1}$	centimole charge per kilogram
CF	Chemical Fertiliser
CIRF	Controlled-Instant Release Fertiliser
CRF	Controlled-Release Fertiliser
DAS	Days After Sowing
DBH	Diameter at Breast Height
FAO	Food and Agriculture Organization
FR	Forest Reserve
g kg^{-1}	gram per kilogram
g mL^{-1}	gram per millilitre
GPS	Global Positioning System
ha	hectare
ISSS	International Society of Soil Science
ITTO	International Tropical Timber Organization
IUCN	International Union for Conservation of Nature
J cm^{-1}	Joule per centimetre

JF	Jellyfish Fertiliser
kg	kilogram
LA _{est}	estimated leaf area
m	metre
MAID	Mean Annual Increment in Diameter
MAIH	Mean Annual Increment in Height
MDF	Mixed Dipterocarp Forest
mg P kg ⁻¹	milligram phosphorus per kilogram
NRCS	National Resources Conservation Service
PC1	Principal Component 1
PC2	Principal Component 2
PC3	Principal Component 3
PCA	Principal Component Analysis
PFE	Permanent Forest Estate
RGR	Relative Growth Rate
RGR _{sh}	Relative Growth Rate of Shoot Height
RGR _{cd}	Relative Growth Rate of Root Collar Diameter
RS	root to shoot ratio
SEF	Soil Evaluation Factor
SF	secondary forest
SFI	Soil Fertility Index
SLF	State Land Forest
SM	<i>Shorea macrophylla</i>
SM96	<i>Shorea macrophylla</i> planted in year 1996

SM97	<i>Shorea macrophylla</i> planted in year 1997
SM98	<i>Shorea macrophylla</i> planted in year 1998
SM99	<i>Shorea macrophylla</i> planted in year 1999
sp.	A single species
spp.	A larger group of species
SPSS	Statistical Software Package for the Social Sciences
STDev	standard deviation
SQ	sturdiness quotient
TPA	Totally Protected Area
TRF	tropical rainforests
USDA	United States Department of Agriculture
WWF	World Wildlife Fund

CHAPTER 1

GENERAL INTRODUCTION

1.1 Research Background and Problem Statements

Tropical rainforests are the most structurally complex and diverse land ecosystems that have ever existed on earth (Whitmore, 1990). Tropical forests in Asia are particularly characterised by the most developed structure and greatest richness of plant and animal life in the world (Whitmore, 1984; LaFrankie, 2005). In Sarawak, Borneo, although the natural forests are classified into five types in accordance to their ecological and physical status, three main types predominate. These are the Hill Mixed Dipterocarp Forest (covering about 9.6 million hectares), the inland Peat Swamp Forest (comprising about 0.75 million hectares) and the coastal Mangrove Forest (occupying slightly more than 0.09 million hectares). The other two types are the *Kerangas* and the Montane Forests which are minimal in size (Forest Department of Sarawak, 2019). The total area of these forests is approximately more than 80% of the land mass of Sarawak (based on 2012 satellite imageries) and according to Bryan et al. (2012), it was found that nearly 80% of the land surface of Sarawak was impacted by previously undocumented, high-impact logging or clearing operations from 1990 to 2009.

Dipterocarpaceae is one of the most important tree families in tropical Asia in terms of ecology and economy (Hattori, 2009a). In Malaysia, tropical rainforests of Sabah and Sarawak have 267 species in 9 genera, is the richest area in the world for dipterocarp species. A general characteristic of tropical rainforests is relatively with high biomass although, in many cases, these forests occur on relatively infertile soils. Vitousek and Sanford (1986) mentioned that this paradox could be explained by the way in which these forests cycle and conserve nutrients.

Forests land regularly succumb to the socio-economic needs of the nation, like many other developing countries. The tropical rainforests have been cleared, burned, logged, fragmented, and overhunted by various anthropogenic activities (Curran et al., 2004). In Sarawak, some forested lands have been excised for rural development and agricultural plantation purposes. Logging of forest areas using mechanical equipment, clear felling, and burning of forest areas for raising agricultural crops are the most severe disturbances in Sarawak context. The practice of shifting cultivation in the permanent forest estates for the cultivation of upland rice, and to a lesser extent, maize, is a great threat to the renewable sources especially in the hill Mixed Dipterocarp Forest (Chai, 1998, Ishizuka, 2001). Notwithstanding, shifting cultivation is one of the most influential anthropogenic actions for tropical rainforests and these abandoned areas of shifting cultivation often turn into unproductive and infertile land causing soil degradation (Hattori, 2009a; Ishizuka, 2001).

Therefore, in 1996, the government of Sarawak had proposed that at least 15% of all the permanent forest estate must be replanted or re-stocked with enrichment planting. Enrichment planting is defined as the introduction of valuable and high quality indigenous species to poorly stocked logged forests without eliminating the existing valuable individuals (Appanah & Weinland, 1993). However, the need for more planting material is inevitable when this proposal is being implemented (Chai, 1998). Enrichment planting in Malaysia has been motivated by the need to improve regenerating forests for future timber production and by the desire to restore and thereby protect degraded unproductive areas (Appanah & Weinland, 1993; Kollert et al., 1996). The success of enrichment planting depends on a wide range of factors, including conditions of the site, species characteristics, the specific planting techniques and treatments applied, as well as social and economic factors (Evans, 1996). Even though there has been extensive silvicultural research for plantation establishment in

the tropics, the information available for planting indigenous tree species in Malaysia remains limited (Appanah & Weinland, 1993; Raja Barizan & Ibrahim, 1998).

According to Kollert et al. (1996), the majority of cases of enrichment planting of native species in Malaysia involve members of the Dipterocarpaceae, the dominant tree family of natural lowland forests. A detailed understanding of the factors controlling seedling survival and growth as well as soil fertility and site quality is required for developing areas of enrichment planting. *Shorea macrophylla* (de Vriese) P.S. Ashton is one of the protected indigenous species under Wild Life Protection Ordinance 1998 and has been selected for reforestation program as well as to be planted in the shifting cultivation area or degraded land in Sarawak. The reason for choosing this species is due to the fact that no other indigenous species in the state can compare with the fruits or illipe nuts it produces and its long-established economic value of the nuts generated as early as 1908 long before the export of timber has started from Sarawak (Chai, 1998). The other reason is due to its fast growing rate. As the seeds of this species are recalcitrant and had short viability (Appanah & Cossalter, 1994; Krishnapillay, 1994), it was impossible to store the seeds for later use. Furthermore, most of these trees are located in the forests and far away from the existing nurseries. Therefore, a readily supply of high-quality seedlings of *S. macrophylla* for large scale reforestation project is not guaranteed nor it can be assured at the moment. Since this species is classified under the International Union for Conservation of Nature (IUCN) Red List of Threatened Species and due to its hardiness, *S. macrophylla* is a prime candidate for rehabilitation efforts in the humid tropics with poor soils.

Nonetheless, central to any successful forest restoration program is the quality of seedlings used in the program (Grossnickle & MacDonald, 2018). Seedling field performance is influenced by both seedling quality and reforestation site conditions.

According to Grossnickle (2005), seedlings may undergo various transplanting stresses before they can initiate growth and become “coupled” into the forest ecosystem (Grossnickle, 2005). In addition, if these environmental stresses are excessive (Grossnickle, 2005) or seedlings are of poor quality (Grossnickle, 2012; Grossnickle & MacDonald, 2018), then poor field performance can occur. Therefore, this is why seedling performance just after planting is pivotal to their survival and growth (Burdett, 1990). Once seedlings enter the establishment phase, their inherent growth potential is related to morphological and physiological attributes (Burdett, 1990) and their ecophysiological response to site environmental conditions (Margolis & Brand, 1990; Grossnickle, 2000), which ultimately determines seedling outplanting performance.

Furthermore, Forest Departments in Malaysia routinely apply nutrients to dipterocarps when planted in secondary, degraded forests (Appanah & Weinland, 1993; Krishnapillay, 2002), but whether the nutrient effects are species- or site-specific remains largely untested. There have been relatively little nutrient limitation experimental tests of dipterocarp seedling growth in the field (Raja Barizan & Ibrahim, 1998). Nursery studies using potted seedlings have revealed that both nitrogen (Yap & Moura-Cousta, 1996; Bungard et al., 2000) and phosphorus addition (Sundralingam et al., 1985; Gunatilleke et al., 1997) may enhance the growth of dipterocarp seedlings (Turner et al., 1993; Burslem et al., 1995). Based on Burslem et al. (1995), whether these results reflect nutrient limitations following outplanting in the field is still unknown. Thus, more detailed field studies which manipulate fertiliser types, composition, and quantity are necessary for *S. macrophylla* plantations in Southeast Asia. This scientific information and knowledge are likely to have a crucial impact on reforestation success as well as for planting stock material and seed production purposes (Kollert et al., 1996).

1.2 Research Questions

The research questions for this study were as follows:

- i. Does the soil fertility in Sampadi Forest Reserve, Lundu, Sarawak affect the survivability and growth performance of planted *S. macrophylla* in this present study?
- ii. To what extent do different types of fertilisers affect seedling performance of *S. macrophylla* at the end of nursery culture prior to outplanting and do the variations in initial seedling age affect the survival and growth of outplanted seedlings in the field?

1.3 Conceptual Framework

In this study, the conceptual framework of assisted natural regeneration strategy for forest rehabilitation and seedling quality assessment were modified from Folk and Grossnickle (1997), Sajise (2003), Grossnickle and MacDonald (2018) (Figure 1.1). Based on the conceptual framework, like any other forest restoration interventions, assisted natural regeneration or known as ANR has three main dimensions including the technological factors (tree improvement), ecological factors (natural resource base) as well as socio-cultural and institutional factors. Therefore, in this study where forest restoration in Sarawak is of concern, one of these dimensions which is the ecological component was adapted for the purpose of enrichment planting of *S. macrophylla* in Sarawak. The first ecological attribute that was chosen for this study was the soil component whereby soil properties in terms of soil morphological and physicochemical properties after enrichment planting of *S. macrophylla* was known. The second ecological attribute was the growth component whereby tree growth assessment after enrichment planting of *S. macrophylla* was clarified.

In order to determine the soil-plant relationship, association between the soil properties and growth performance of planted *S. macrophylla* was conducted. Seedling morphological quality assessment of *S. macrophylla* in terms of nursery and field trials describing the relationships between material attributes, performance attributes, initial survival potential and field performance potential were also determined.

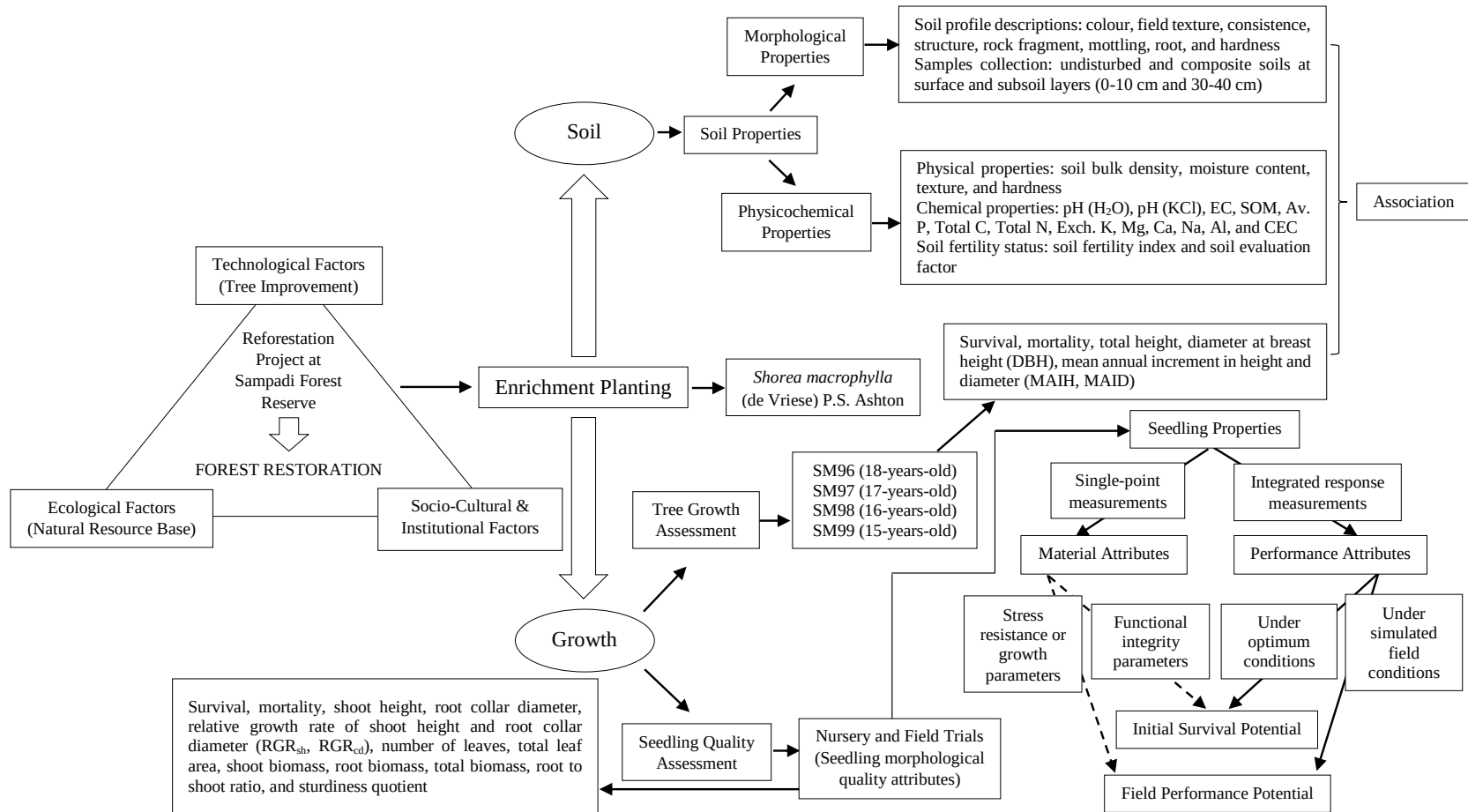


Figure 1.1: Conceptual framework of assisted natural regeneration strategy for forest rehabilitation and seedling quality assessment describing the relationships between material attributes, performance attributes, initial survival potential, and field performance potential [modified from Folk & Grossnickle (1997); Sajise (2003); Grossnickle & MacDonald (2018)].

1.4 Objectives of the Study

Appropriate rehabilitation or reforestation techniques are necessary for each type of forest condition, especially under the tropical climate in Sarawak, Malaysia. In Sarawak, one of the reforestation techniques adopted by the Forest Department of Sarawak to rehabilitate the tropical rainforest ecosystem is by enrichment planting. Since dipterocarp species has been identified as one of the valuable indigenous timber tree species which benefits future reforestation and rehabilitation efforts in Sarawak, it is very crucial to conduct study on the evaluation of growth performance and soil properties of planted indigenous tree species under artificial ecosystem after 15 to 18 years of its establishment as well as in seedling production for restoring the tropical rainforest ecosystems of Sarawak, Malaysia.

Taking into consideration the statements and research questions, the five main objectives of this present study were as follows:

- i. To assess the preliminary soil morphological and physicochemical characteristics of the planted forests under reforestation in comparison to an adjacent secondary forest
- ii. To evaluate and compare the current status of survival and growth performance of *S. macrophylla* under line planting system for reforestation and rehabilitation purposes
- iii. To determine the status of soil physicochemical properties under enrichment planting in comparison to an adjacent secondary forest as well as to evaluate the effect of enrichment planting of *S. macrophylla* on the soil fertility status with special reference to Soil Fertility Index (SFI) and Soil Evaluation Factor (SEF)
- iv. To determine the influences of inorganic and organic fertilisers on the seedling morphological quality attributes of *S. macrophylla* in a tropical nursery as to produce healthy and quality seedlings in ensuring better field performance

- v. To investigate the effects of initial seedling age on the subsequent outplanting performance of *S. macrophylla*

1.5 Scope of the Study

The scope of this present study in the form of a conceptual framework is presented in Figure 1.1. Field and laboratory studies were conducted to determine the status of soil morphological and physicochemical properties at reforestation sites after enrichment planting of *S. macrophylla* in comparison to an adjacent secondary forest. Soil morphological properties were determined by conducting the soil profile descriptions in each of the representatives' reforestation sites and secondary forests. Following that, undisturbed and composite soil samples at the surface (0-10 cm) and subsurface layers (30-40 cm) were collected for soil physicochemical analysis. Next, the current status of the survival and growth performance of planted *S. macrophylla* trees after enrichment planting by line planting technique were assessed. After that, the association between soil fertility (with special reference to soil fertility index and soil evaluation factor) and tree growth performance after enrichment planting were determined. In order to produce high-quality seedlings with desirable attributes and meet successful forest restoration program in the tropics, a seedling quality assessment was set to determine the influences of inorganic and organic fertilisers on the morphological quality attributes of *S. macrophylla* seedlings in a tropical nursery. Finally, the effects of initial seedling age were investigated on the subsequent outplanting performance in the field.

CHAPTER 2

LITERATURE REVIEW

2.1 Current Status of Tropical Rainforests in South East Asia

Tropical rainforests of Malaysia are located in South East Asia and comprises of Sabah and Sarawak on the island of Kalimantan (Borneo) and Peninsular Malaysia. In the case of total forest cover in Malaysia, it has been estimated to be 20 million ha or 60% of its total land area, with the proportion of forested land being higher in Sabah and Sarawak as compared to Peninsular Malaysia. Of the total forest area, 5.97 million ha are in the Peninsular Malaysia, 4.25 million ha in Sabah and 9.84 million ha in Sarawak (Jomo et al., 2004). Food and Agriculture Organization (2014) through Global Forest Resources Assessment 2015 reported Malaysia's detailed status of forests from the year 1990 - 2012, as referred in Table 2.1.

In Sarawak, forests have been classified into three main categories namely the Permanent Forest Estate (PFE) which comprises of Gazetted Forests namely Protected Forests, Forest Reserves, and Communal Forests; Totally Protected Area (TPA) such as National Parks, Wildlife Sanctuaries and Rehabilitation Centre; State Land Forest (SLF) whereby the forest land not reserved permanently as forests, can be alienated for other land uses as shown in Table 2.2 and other land uses including agriculture land, urban land, and native customary land.

According to Food and Agricultural Organization (2005), it was estimated that the world's forest is lost and decreasing annually at the rate of 13.5 million ha, mainly due to clearing for plantation or agriculture and shifting cultivation. Malaysia's total forest area decreased by 434 000 ha between 2005 and 2010 (an annual decline of 0.42%) and by 1.92

million ha between 1990 and 2010 of the estimated 17.1 million ha of dry inland forests, 5.48 million ha are in Peninsular Malaysia, 7.83 million ha are in Sarawak, and 3.84 million

Table 2.1: Malaysia's detailed status of forests (1990 - 2012).

National 2015 Categories	Area (1000 Hectares)					
	1990	2000	2005	2010	2011	2012
(a) Permanent Reserved Forest (PRF)						
- Peninsular Malaysia	4,750	4,800	4,800	4,920	4,912	4,894
- Sabah	3,350	3,600	3,600	3,607	3,607	3,609
- Sarawak	4,500	6,000	6,000	6,000	6,000	6,000
Total PRF	12,600	14,400	14,400	14,526	14,519	14,503
(b) State Land Forest	6,820	4,640	4,141	4,718	4,630	4,656
(c) National Parks and Wildlife & Bird Sanctuary						
	1,120	1,120	1,120	1,859	1,859	1,859
Total Forested Area (a + b + c)	20,540	20,160	19,661	21,104	21,009	21,019
(d) Rubber Plantation	1,836	1,431	1,229	1,020	1,023	1,042
Total Rubber Plantation (d)	1,836	1,431	1,229	1,020	1,023	1,042
(e) Other Land:						
- Oil Palm	2,029	3,377	3,802	4,854	5,000	5,077
- Agriculture Crops	1,461	1,007	959	848	861	861
- Urban and Other Uses	6,844	6,735	7,259	5,022	4,955	4,849
Total Other Land (e)	10,334	11,119	11,820	10,724	10,816	10,787
Inland Water Bodies	120	120	120	424	424	424
Total Area for Country	32,830	32,830	32,830	33,272	33,272	33,272

(Source: Food and Agriculture Organization, 2014)

Table 2.2: Current land use of Sarawak.

Land use	Total land area (million ha)
Permanent Forest Estate	6.0
(Forest Plantation)	2.8
(Natural Forests)	3.2
Totally Protected Areas	1.0
State land Forest	2.8
Plantation (Oil Palm + Agriculture)	2.3
Others (Development)	0.3
Total Land Area	12.4

(Source: Sabal Agroforestry Centre, 2011)

ha is in Sabah (International Tropical Timber Organization (ITTO), 2011). Besides forest harvesting and forest encroachment, shifting cultivation is one of the major causes of land degradation in Sarawak. ITTO (2011) reported that 2.25 million ha were under shifting cultivation in the 1960s and by 1985 increased to 3.33 million ha. The reduction and degradation caused by anthropological activities affected not only the sustainable production of timber but also the global environment. Reduction of these tropical forests has an impact on global warming in two ways; acceleration of greenhouse gas emissions, such as carbon dioxide, methane, and nitrogen oxides as well as reduction in sequestration of carbon by tropical trees like *Dipterocarpus* spp. during photosynthesis (Kira, 1991). Natural disasters such as flooding, erosion, landslides, and desertification have increased dramatically due in part to the degradation or loss of tropical forest (Tanouchi, 1989; Kobayashi, 2004). Nihonchousakai (1989) stated that approximately more than 20% of the topsoil on the world's arable land has been lost during the past 40 years and desertification is progressing at a rate of 6 million ha per year.

Rautner (2005) pointed out that the Borneo's forests are disappearing at a very fast rate as compared to the percent of total forest land area in the mid-1980s. Only about 50.4% of Borneo is still forested as compared to 73.7% and 57.5% in the year 1985 and 2000, respectively. This shows that the current deforestation rate for Borneo is very alarming. Jomo et al. (2004) added that logging of trees for economic purpose of timber has undoubtedly been the major causes of destruction of tropical rainforests in Sarawak.

Forest harvesting for timber purpose affects the structure of forest and environment. It is estimated that the growth and regeneration rates of trees has declined in the tropics for reasons such as degradation of natural forest, erosion, landslides, and greenhouse impacts. However, severity of harvesting impacts on forest ecosystem vary with time, logging

methods, soil characteristics, topography, local rainfall patterns, and mode of timber transportation (Kobayashi, 1982; Stone, 1984). According to Froelich (1983) and Gent (1984), many studies have examined the impact of forest harvesting on soil physical properties which include reduced saturated hydraulic conductivity, coarse porosity and total porosity, as well as increased bulk density. Nonetheless, soil chemical properties also changed with decreasing total carbon, total nitrogen, and exchangeable cations caused by organic matter decomposition and run-off from ecosystems (Kobayashi, 1994). Thus, changes both in physical and chemical properties of the soil reduce the soil productivity of forest and the growth of trees.

2.2 Reforestation Efforts and Various Studies on Rehabilitation of Degraded Areas in Tropical Region of Malaysia

Reforestation refers to the establishment of plantations for individual and non-industrial uses and does not include natural regeneration of old tree crops (Lamb, 1994). Reforestation in the broad sense implies the rehabilitation or reclamation of degraded land which usually involves either planting indigenous or exotic tree species. Sarawak Forest Department initiated its reforestation program in 1979. In the broadest term, the purpose of the reforestation effort was to reforest shifting cultivation and degraded areas within permanent forest estates to productive forests in order to reach sustainable forest production in the future. Forest Department of Sarawak (1999) reported that over the period of 20 years since the establishment of the reforestation program, the total area which had been reforested was about 18,969 hectares, consisting 2,222 hectares of rattan species and 16,747 hectares of timber species (Table 2.3).

In Sarawak, *Shorea macrophylla* was reported as most popular planted species for the purpose of reforestation activities. From 1979-1999, a total of 7,314.4 hectares of *S. macrophylla* has been planted in Sarawak.

Table 2.3: Comparison of *S. macrophylla* with other tree species under reforestation program in Sarawak (1979 - 1998).

No.	Timber Species	Local Name	Area (ha)
1	<i>Shorea macrophylla</i>	<i>Engkabang jantung</i>	7,314.4
2	<i>Acacia mangium</i>	<i>Acacia</i>	3,592.8
3	<i>Dryobalanops</i> spp.	<i>Kapur</i>	1,773.6
4	<i>Durio zibethinus</i>	<i>Durian</i>	1,115.7
5	<i>Shorea pinanga</i>	<i>Engkabang langgai bukit</i>	996.7
6	<i>Hevea brasiliensis</i>	<i>Rubber/ Getah</i>	71.6
7	Other <i>Shorea</i> spp. (6)		143.5
8	Others species (27)		1,738.9
TOTAL			16,747.0

(Source: Forest Department of Sarawak, 1999)

According to Sakurai et al. (1999), several enrichment plantings which cover an area size of about 20 ha had been conducted in Bakam Experimental Reserve, Niah Forest Reserve, Miri, Sampadi Forest Reserve, and Sabal Forest Reserve. On the other hand, the rehabilitation efforts on degraded land were carried out at Gunung Gading National Park, Gunung Selang Forest Reserve, Semengoh Forest Reserve, and Balai Ringin Protected Forest (Sakurai et al., 2006).

Apart from that, several joint research projects on rehabilitation of the tropical rainforests were initiated and implemented in Bintulu by Forest Department of Sarawak, Universiti Putra Malaysia, and Yokohama National University, Japan. Besides, Malaysian-Japan Friendship projects such as Yokohama-Sarawak Friendship Forest Project at Kubah National Park, Hiroshima-Sarawak Friendship Forest Project at Balai Ringin Protected Forest and Oita-Sarawak Friendship Forest Project at Sampadi Forest Reserve were

conducted as well for reforestation and rehabilitation purposes. An area of 300 hectares was allocated for tree planting program in Balai Ringin Protected Forest and 25 hectares of affected shifting cultivation area in Kubah National Park. The area was planted with tree species including *Shorea macrophylla*, *Dryobalanops beccarii*, *Azadirachta excelsa*, and *Calophyllum teysmanii* using line planting method by the volunteers in 1997, 1998, and 1999.

In addition, an area of 6.9 hectares in Sampadi Forest Reserve at the Lundu Division was allocated for Oita-Sarawak Friendship project whereby the project gathers participants from students and 16 teachers from Mie Agriculture High School. According to Forest Department of Sarawak (2009), the area was planted over a period of 5 years from 1996 to 2000. In 1996, 1.6 hectares were planted with *S. macrophylla* while in 1997 and 1998, 1.1 and 1.2 hectares, respectively were planted. In August 1999, another 1.3 hectares were planted. Such reforestation and rehabilitation efforts are especially significant in reforesting small areas deforested by shifting cultivation within the permanent forest estate and totally protected areas which would not be of economic size for big-scale operators for forest plantation establishment.

In North Ulu Segama, Sabah, reforestation activities to restore the tropical rainforests were also conducted to address the rapid deforestation rate. ITOCHU Corporation collaborated with the Forestry Department of Sabah to carry out reforestation of an area of approximately 2,400 hectares. As in Peninsular Malaysia, reforestation activities and rehabilitation of forest land had been conducted at Ayer Hitam Forest Reserve, Chikus Forest Reserve, Pasoh Forest Reserve, and Bukit Kinta Forest Reserve (Arifin et al., 2008; Hamzah et al., 2009). However, there was lack of information available on the ecological suitability

of planted tree species for reforestation activities since these reforestation efforts were only conducted on experimental basis and in small scale.

The success of reforestation can be viewed as a continuum from the successful establishment of the initial planting through to maturation and realisation of full environment and how much does the forest benefit in terms of socio-economics (Reay & Norton, 1999). In order to evaluate the success of reforestation, there are several number of indicators need to be considered. The most common indicators used for measuring establishment success are the survival rate of planted trees and planted area compared to target area (Nawir et al., 2007). It takes the greatest challenge among developing countries to ensure a long-term success in reforestation. Le et al. (2011) added that holistic and integrated approaches are needed in order to establish the success of reforestation.

2.3 Planting Techniques for Reforestation in Regenerating Tropical Rainforests

There are various methods used to restore the degraded tropical rainforests in Malaysia. The most common tree planting methods practiced for reforestation purpose is the enrichment planting technique. Under this enrichment planting technique, there are several types of plantings such as line planting method, gap planting method, patch and cluster or nest planting method, and island-corridor planting method. Other planting methods are also available such as open space planting techniques which include open space planting and multi-storied forest planting.

2.3.1 Enrichment Planting Technique

Enrichment planting, which is a typical planting method in Malaysia, generally has been carried out for restoration of degraded vegetation types and for future timber stocks through

introduction of lacked tree species such as dipterocarp under degraded vegetation associated with shifting cultivation or logging (Appanah & Weinland, 1993; Ådjers et al., 1995; Vincent & Davies, 2003). According to Appanah and Weinland (1993), enrichment planting is defined as the introduction of valuable and high quality indigenous species to poorly stocked logged forests without eliminating the existing valuable individuals. Enrichment planting is a highly effective technique for the rehabilitation or reforestation of degraded vegetation (Appanah & Weinland, 1993; Kenzo et al., 2008). Enrichment planting in Malaysia has been motivated by the need to improve regenerating forests for future timber production, and by the desire to restore and thereby protect degraded unproductive areas (Appanah & Weinland, 1993; Kollert et al., 1996). For developing areas of enrichment planting, a detailed understanding of the factors controlling seedling growth and survival is required. The relationship between dipterocarp seedling performance and light availability has been studied in numerous species and is reasonably well known (Ashton et al., 1997). As saplings, potential plantation dipterocarp species vary from moderately to very shade tolerant. In field trials, rates of dipterocarp growth and survival are consistently better in moderate light levels than in the understory of either primary or secondary forest (Raja Barizan & Appanah, 2000). The advantage of enrichment planting is that local vegetation of pioneer tree species such as *Macaranga gigantea* can provide optimal shade condition for dipterocarp which is well known as shade tolerant when they are sapling (Ådjers et al., 1995). Ådjers et al. (1995) stated that among the principal species used in enrichment planting is the common, faster growing, and shade tolerant dipterocarps such as *Shorea macrophylla*, *Parashorea tomentella*, *Dryobalanops beccarii*, and *Dryobalanops lanceolata*.

2.3.1.1 Line Planting Technique

Line planting is the most popular technique to enrich secondary forests in the absence of seedlings and saplings on the forest floor. It derives its name from the line clearing and plantation of commercial species (Kobayashi, 1994). According to Lamprecht (1989), the best known enrichment planting is line planting which has a number of variants throughout the tropics. It is significant to determine the width and the direction of line. For example, if the width of the line is narrow, regeneration of pioneer vegetation and residual secondary forest cover the line quickly due to the vigorous recovery of the vegetation in the tropics. Therefore, the lines are determined from an East to West direction and are 10 m in width to ensure an adequate supply of sunlight (Kobayashi, 1994). Decisions on line width and time of line opening are matters for research in particular sites with a particular group of species.

An example from a 15-year trial in Tapah Hill Forest Reserve, Malaysia, showed that different times of girdling to open the canopy have different effects on the growth performance of the dipterocarp seedlings planted. The treatment adopted for the trial was poison-girdling of all trees within a zone of 0.9 to 1.8 m on either side of the planting lines. Based on the result, it was recommended to open the canopy at the time of planting or at three months after planting (DANIDA, 2005). In Bakam Forest Reserve, line planting method and cluster or nest planting method was used for tree planting (Sakurai et al., 1999). Manual slashing of the undergrowth plants along the planting lines was conducted. Lines were cut 5 m apart and tree seedlings were planted at 5 m interval along the line (Sakurai et al., 1999). Appanah and Weinland (1993) reported that line planting method and gap planting method are not widely practiced in Peninsular Malaysia due to the high cost of regular maintenance of both the planting methods. Figure 2.1 shows the lay-out of the line planting technique.

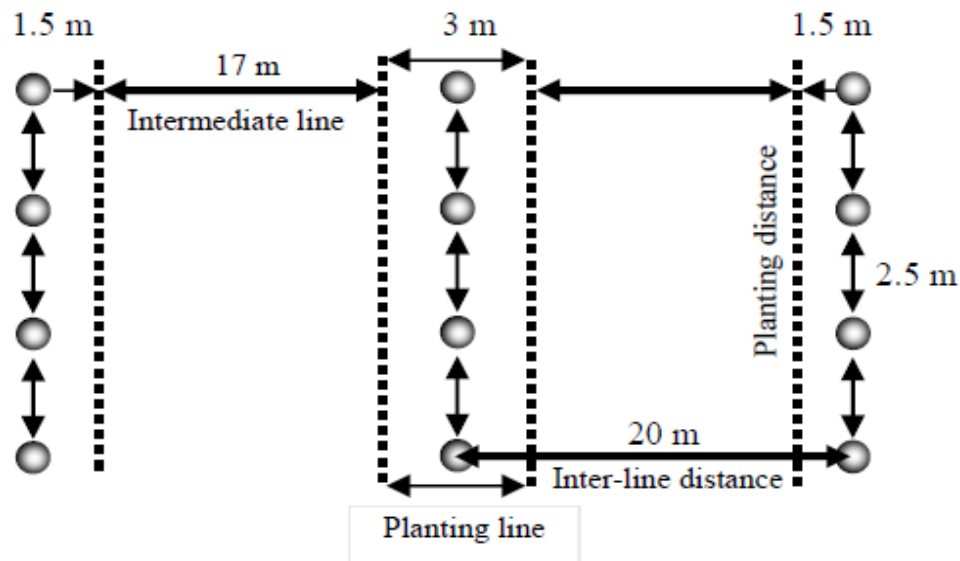


Figure 2.1: Line planting method.

(Source: Pamoengkas, 2010)

2.3.1.2 Gap Planting Technique

Tropical rainforests consist of a mosaic of patches at different stages of maturity from gaps, through stands of small saplings or poles, to mature high forests. The forest regenerates itself through the formation of the gap (Whitmore, 1984). Gap planting involves the planting of seedlings in artificially created gaps. Ochiai (1990) described that the gap created by hole cleaning must be wide enough for seedlings to receive sufficient sunlight and must be created on a suitable site where the seedlings are planted in the area. The seedlings in the gap received enough sunlight to grow quickly if the gap size is equal to the height of the upperstory (Ochiai, 1990). Hamzah et al. (2009) stated that open space planting, lines or gaps planting shows much better result of the growth and survival rate of dipterocarp species because dipterocarp species are shade tolerant. In addition, gap planting has also been found to be more efficient and effective than line planting in terms of cost and keeping the undergrowth suppressed. This type of planting technique is also used in logged-over forests

and usually applied where there are no seedlings of commercial species. Both line planting and gap planting are suitable methods but it has been recommended that line planting provides less favorable light conditions for seedling growth as compared to gap planting (Figure 2.2).

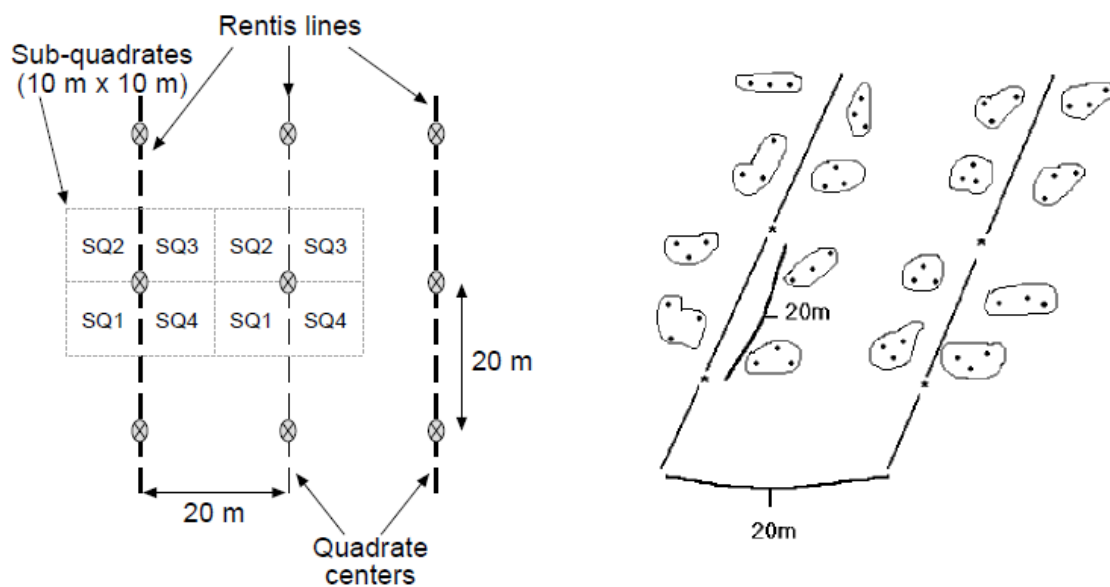


Figure 2.2: Gap planting method.

(Source: Garcia & Falck, 2003)

2.3.1.3 Open Space Planting Technique and Multi-Storied Forest Planting

As for open space planting, areas are clear cut and the seedlings are planted in open space without shade from pioneer species. In open areas, fast growing native species such as *Laran* or known as *Kelampayan* (*Neolamarckia cadamba*) and *Binuang* (*Octomeles sumatrana*) can be planted. On the other hand, multi-storied forest planting is a promising rehabilitation technique to promote forest development and management in the tropics, which can convert marginally poor forest into forest plantation and to replace the exotic species into indigenous high quality timber species in order to meet future demand of general utility timber

(Heriansyah et al., 2011). For multi-storied forest planting, seedlings are planted in open space as well but after several years of seedling growth, they are able to provide shade and new seedlings will be planted in between the already planted seedlings. According to Heriansyah et al. (2011), both of these techniques are practiced in logged-over forests.

A study on the effect of planting type of multi-storied forest management on growth characteristics was established in Chikus Forest Reserve, Perak in 1992 (Figure 2.3). According to Heriansyah et al. (2011), in November 1989, the Chikus Forest Reserve was completed after clear felling and burning of the area and it was planted with 900 seedlings per hectare of *Acacia mangium* at a spacing of 3.0 m x 3.7 m. Since the multi-storied forest management project started in November 1991, 500 hectares of *A. mangium* plantation was clear-felled in lines and indigenous high quality timber species such as *Shorea leprosula* was planted. The remaining *A. mangium* trees were expected to play a significant role as shade trees to the indigenous trees planted.

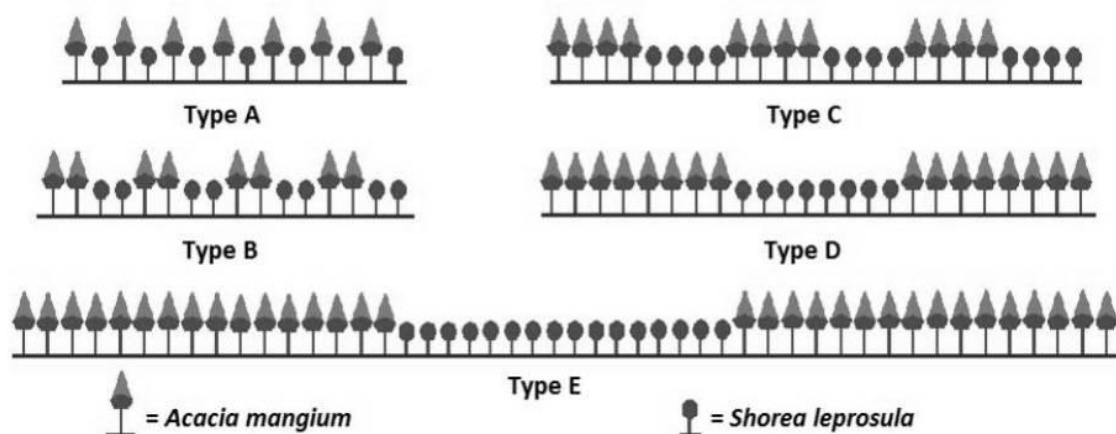


Figure 2.3: Multi-storied forest planting designs.

(Source: Heriansyah et al., 2011)

2.3.1.4 Patch and Cluster/ Nest Planting Technique

For patch and cluster or nest planting technique, the seedlings are distributed randomly around the mother tree. These seedlings are unable to receive sufficient sunlight because upper trees prevent sunlight from reaching them on forest floor. According to Kobayashi (1994), the substory and understory of non-commercial species are cleared in order to improve light conditions for the seedlings (Figure 2.4). This treatment is known as “Forest Patch Improvement”.

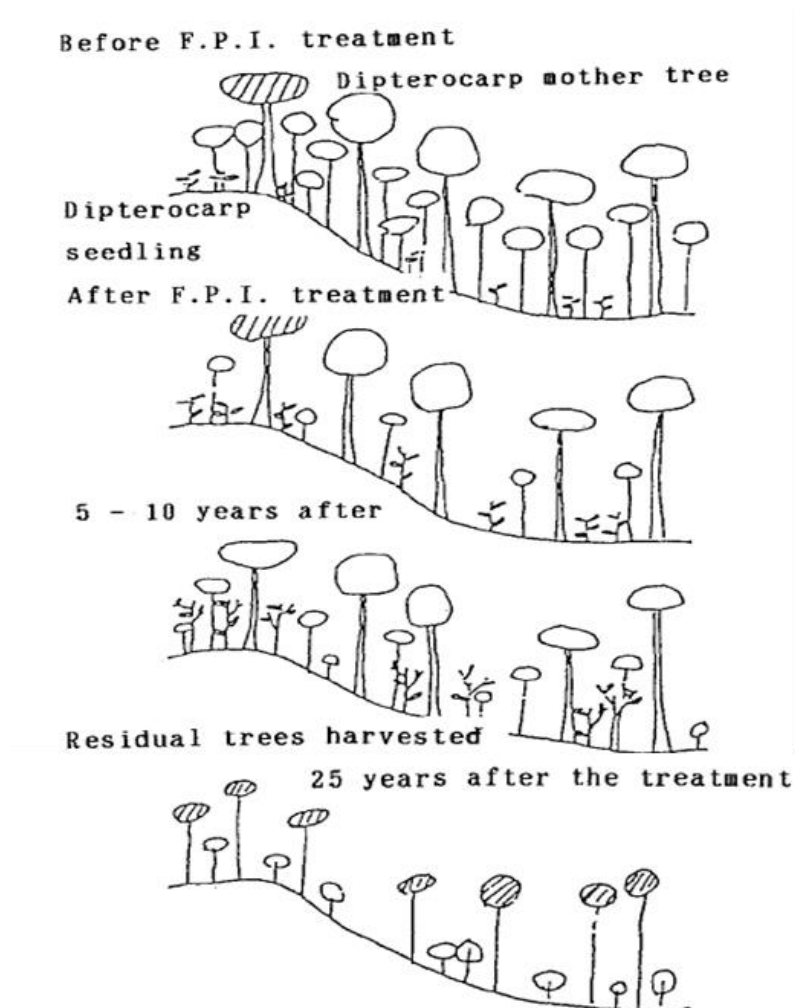


Figure 2.4: “Forest Patch Improvement” scheme in a logged over mixed dipterocarp forest as accelerating natural regeneration.

(Source: Kobayashi, 1988)

Usually, the size of clearing is dependent on the area of seedling distribution whereby the survival and growth rate of the seedlings should be increased. When the seedlings grow to a height of 3 m to 4 m, the upperstory will be harvested for commercial use. Kobayashi (1988) and Ochiai (1990) reported that the “Forest Patch Improvement” treatment is considered effective in decreasing mortality and increasing the growth rate of seedlings in mixed dipterocarp secondary forest and peat swamp forest. Some of the seedlings in the treatment area disappear from the forest floor and this represents the heterogenetic response of the small area against the treatment. In order to increase the treatment effects, the substory will be carefully cleared and the intensity of the treatment will be increased until the relative light intensity reaches more than 30% (Kobayashi, 1988). This treatment should be carried out when newly germinated seedlings have been established.

A previous study at Bakam Experimental Reserve (BER) on the ecosystem rehabilitation, especially for the ecosystem initiation by tree planting of indigenous species was reported by Sakurai et al. (1999). Two types of plantation were established at Bakam Experimental Reserve namely the line planting and patch and cluster or nest planting. For patch and cluster or nest planting, twenty-seven base lines were prepared (Figure 2.5), where 999 patches and 606 clusters or nests were placed (Figure 2.6) on 12.6 ha (6.3 ha each in the northern and southern part of the line planting site).

2.3.1.5 Island-Corridor Planting Technique or Scheme

Island-Corridor Planting Technique or Scheme is an improved tree planting scheme by taking into account the successful results of Patch and Cluster or Nest method of tree planting (Ninomiya et al., 2000). The Island-Corridor Planting Scheme is composed of Island of Patch Planting with 2 m x 2 m spacing and Corridor of Cluster or Nest Planting. Artificial

planting by using this technique is also one of the practical ways to initiate a forest for ecosystem rehabilitation. A study on an experimental reforestation planting at Niah Forest Reserve was reported by Ninomiya et al. (2000) in February 2000. Seedlings of dipterocarp and other indigenous tree species (20 species, 26,316 individuals) were planted by the “island-corridor planting scheme” in the site. Thirty-six seedlings (single species) were planted in a 14 x 14 m² called “island” with 2 x 2 m intervals (Figure 2.7). Meanwhile, in the rectangular “corridor” measuring 3 x 36 m, four seedlings (single species) were planted closely and seven gatherings were distributed at intervals of 5 m (Figure 2.7) (Ninomiya et al., 2000).

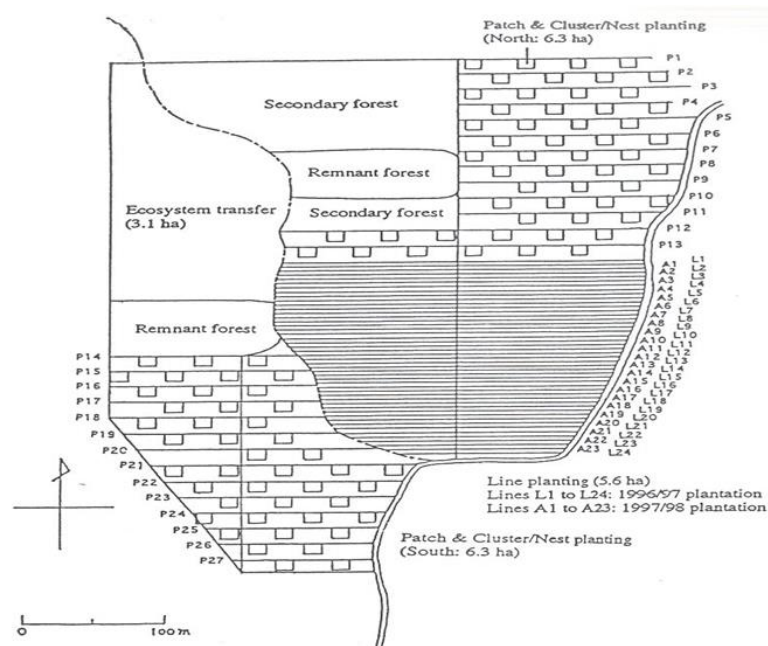


Figure 2.5: Arrangement of experimental plot in Bakam Experimental Reserve.

(Source: Sakurai et al., 1999)

2.4 Soils and Its Properties in Sarawak, Malaysia

In Malaysia, many of the soils in the tropical regions especially those in the secondary forest could be considered as moderately to strongly weathered soils with strong acidity (Sakurai, 2004). In general, since Malaysia has a humid tropical climate; the rate of weathering is high. Thus, there is a substantial area of land with highly-weathered soils. These are normally formed through the *in-situ* weathering of igneous and high-grade metamorphic rocks as well as sedimentary and low-grade metamorphic rocks. These sedentary soils, with well-developed soil horizons, tend to be varied in depth, but slightly acid and quite infertile. Generally, they occupy the central part of Peninsular Malaysia and the interiors of Sarawak and Sabah.

Nieuwolt et al. (1982) stated that, the soils of Malaysia can be divided broadly into two groups namely the sedentary soils formed in the interior on a wide range of rock types, and the soils of the coastal alluvial plains. The sedentary soils are developed on igneous, sedimentary, and metamorphic rocks, and are strongly weathered with mostly kaolinitic clay minerals. The distribution of such soils is very extensive especially on the hill and mountain excluding lowland and coastal areas. Ferralsols, Fluvisols, Gleysols, Luvisols, Nitisols, Lithosols, Regosols, Cambisols, and Histosols are among the major soil types in the tropical region of Malaysia (Deratil & Donson, 1994). Among them, the most extensive are Lithosols, Regosols, and Cambisols which occupy 58% of the land area. The sedentary soils fall under the classification order of Nitisols, Acrisols, and Ferralsols (Ultisols, Oxisols) whereas the coastal alluvial soils fall under the categories Gleysols, Cambisols, and Podzols (Entisols, Inceptisols, and Spodosols). High content of exchangeable aluminium together with high activity of clay shows strong acidity in Alisols soils. On the other hand, Ferralsols, Nitisols, and Acrisols contain low activity of clay with certain amount of exchangeable

aluminium. In this case, acidity due to the existence of exchangeable aluminium would be the strongest constraint for crop cultivation together with low fertility caused by strong weathering. In addition, tropical region especially those in the inland and upland areas are universally utilised for various land use activities such as agriculture and forestry activities, and therefore, regeneration of the forest stands after series of land use could lead to longer period of forest recovery.

In Sarawak, there are montane and peat swamp forest which both having the organic soil but differ in the morphological properties and surface vegetation. According to Ismawi et al. (2012), peat swamp forests of Sarawak have vegetative and edaphic characteristics similar to those in Sumatra and Peninsular Malaysia which is predominantly organic matter built up behind mangrove swamps. They are ombrogenous, or rains fed, and are recent in origin (Morley, 1981). After a longer time of period, the organic matter builds up and peat deposits can extend up to 20 m in the forest layer. Ismawi et al. (2012) pointed out that, usually they occur in three geomorphic situations namely lowland coastal swamps, inland swamps and valleys, and high altitude which are free draining situations and highland swamps. In Sarawak, peat soils occur in large basin swamps and in small interior valleys that have developed in comparatively recent times (Andriesse, 1988). In addition, Mutalib et al. (1992) reported that the morphological characteristics of lowland organic soils are quite similar throughout the region and the convexity of coastal and deltaic peat swamps surfaces are increasingly pronounced with distance from the sea.

Meanwhile, in Sampadi Forest Reserve, the soil is moist and wet due to the poor drainage of water from the rain. Based on personal communication with the Forest Department officer, annual flooding in the nearby river known as *Batang Kayan* (*Sungai*

Kayan) will easily rise up and flood the nearby forest. Due to the lack of ability to absorb water efficiently by soil, the flood will last for several days and these will moisten the soil in the area. In the long run, it will lead to the built up of organic matter on the forest layer. According to previous study conducted by Ismawi et al. (2012) on peat soils, peat swamp forests form when sediments build up behind mangroves as rivers drain toward the coast and after a longer time of period, deposition of organic matter occur and the peat deposits up to certain thickness in the forest layer.

According to Aragao (2009), soil types are highly variable in the tropics due to a combination of several variables such as climate, vegetation, topographic position, parent material, and soil age. Although most tropical soils are characterised by significant leaching with poor nutrients, however there are some areas that contain fertile soils. Moran et al. (2000a, 2000b) stated that succession of forest plays a vital role in soil restoration through accumulation of biomass, build-up of litter and organic matter, and other beneficial soil and plant interactions. Since most soils in the tropical regions are infertile, and once the forests have been cleared and being utilised continuously, depletion of organic matter in the surface soil by both decomposition and soil erosion as well as acceleration of soil acidification in the subsurface soils proceed quickly due to high temperature, humidity, and heavy rain. These results in rapid loss of nutrients which would consequently lead to degradation on the soil in the tropics (Wasli et al., 2009).

2.5 Importance of Soil Physicochemical Properties for Reforestation of Tropical Rainforest Ecosystems

An assessment of forest rehabilitation program in relation to soil fertility status by using soil indices could provide fundamental information on soil suitability for species preferences and

improve the effective technique for future rehabilitation program in tropical rainforests. According to Arifin (2007), the assessment of soil fertility and site quality is crucial in forest management because it reflects to the productive capacity of the forest area to support plant growth. Soil physical properties profoundly influence how soils function in an ecosystem and how they can be best managed (Brady, 2008). The physical properties of soils such as texture, structure, bulk density, porosity, aeration, strength, temperature, and colour are dominant factors which affect the use of a soil. According to Duane (2008), these properties determine the availability of oxygen in soils, the mobility of water into or through soils, and the ease of root penetration. Moreover, the physical properties of soils determine their adaptability to cultivate and the level of biological activity that can be supported by the soil. Sanchez (1976) reported that soil physical properties changed because of the effect of land use system and its management such as intensity of cultivation, the instrument used, and the nature of the land under cultivation, rendering the soil are less permeable and more susceptible to runoff and erosion losses.

Duane (2008) defined bulk density as the density of a volume of soil as it exists naturally, which includes any air space and organic materials in the soil volume. Measurement of soil bulk density is significant for determination of compactness, as a measure of soil structure, for soil pore space calculation as well as an indicator of aeration status and water content. Bulk densities of soil horizons are inversely related to the amount of pore space and soil organic matter (Brady & Weil, 2002; Gupta, 2004). Besides that, bulk density is influenced by the content of organic matter. Alexander (1989) reported that higher organic matter content consequently decreased the value of the bulk density of the soils. On the other hand, soil porosity is known as a void fraction where it is the measurement of empty or void spaces in soil and generally computed as the fraction of

the volume of emptiness over total volume of the soil. Root elongation increases soil porosity. According to Tan (2005), the pore in the soils develops due to the penetrations of roots, worms, and other forms of soil life.

Soil texture is often considered to be the most important diagnostic soil characteristics in determination of physical and chemical properties of soils. It greatly affects the infiltration and retention of water, soil aeration, absorption of nutrients, microbial activities, tillage, and irrigation practices (Foth, 1990; Gupta, 2004). According to White (1997), the rate of increase in stickiness or ability to mould as the moisture content increases depend on the content of silt and clay and the degree to which the clay particles are bound together into stable granules and the organic matter content of the soil. A coarse, sandy soil is easy to till, has plenty of aeration for good root growth, and is easily wetted but it also dries rapidly and easily loses plant nutrients, which are drained away in percolating water. On the other hand, high-clay soils have very small particles that fit closely together and have greater water holding capacity than sandy soils. However, a clay-rich soil structure can hold nutrients in the soil for a long time, but coarse sand-rich soil structure permits nutrients to leach rapidly (Lu et al., 2002). The ability to hold and exchange needed nutrient elements with plant roots depends on the amount of clay and organic matter content which a soil basically contains.

Soil organic matter is also one of the critical components contributing to a soil's ability to carry out necessary environmental functions such as supplying plant nutrients and facilitating soil aggregation. Paniagua et al. (1999) stated that soil organic matter is regarded as the single most important indicator of soil fertility and a major component in the assessment of soil quality in the tropical regions. A study by Yaacob (1979) reported that the organic matter and nitrogen are two of the most important constituents of Malaysian soils

where they influence many physical, chemical, and biological properties and reactions, many of which influence their overall fertility and crop production. In addition, Yaacob (1979) clarified that the soil organic matter and nitrogen content varies with topography, vegetation, and depth. The organic matter and nitrogen contents of some selected ecosystems in Malaysia are shown in Table 2.4.

Table 2.4: Organic matter and nitrogen contents of soils under selected ecosystems in Peninsular Malaysia.

Ecosystem	Organic matter Depth (cm)	% Organic matter	% Nitrogen	pH
1) Virgin forest	0 – 6	5.82	0.27	4.24
	6 – 15	2.54	0.13	4.43
2) Regenerated forest	0 – 6	2.81	0.13	4.30
	6 – 15	1.35	0.08	4.55
3) Plantation	0 – 6	4.01	0.16	4.74
	6 – 15	2.50	0.10	4.80
4) Abandoned sites	0 – 6	2.66	0.13	4.74
	6 – 15	1.52	0.10	4.70
5) BRIS soil	0 – 6	1.56	0.05	4.80
	6 – 15	0.49	0.03	5.00
6) Peat soil	0 – 6	91.4	1.72	4.60
	6 – 15	95.6	1.41	4.30

(Source: Coulter (1950), Parbery & Venkatachalam (1964))

According to Coulter (1957), Anderson (1964), and Allen & Coulter (1956), mineral soils under virgin forest have high organic matter and nitrogen content than other ecosystems but however the highest was found in peat soils which cover nearly more than two million hectares in Peninsular Malaysia, Sabah, and Sarawak. In alluvial soils, organic matter and nitrogen contents vary with the texture, source of the parent materials and cropping practices (Yaacob, 1979).

In soil, chemical reactions which occur affect the processes leading to soil development and soil fertility build up. Minerals inherited from the soil parent materials

overtime release chemical elements that undergo various changes and transformations within the soil. According to Duane (2008), soil pH is an indication of the acidity or basicity of the soil, which is caused by particular chemical, mineralogical, and/or biological environment. In the humid tropical region, due to high temperature and humidity, nutrients are easily lost through soil erosion and leaching, leading to acidic soil. Notwithstanding, many soil properties and processes are affected by pH, such as clay mineral formation and microbial activity. Some available nutrients are deficient if soil pH is below 6.0 (Tan, 2005). Besides that, the acidity occurring in the forest soils was due to the presence of aluminium and hydrogen ions. Both of the aluminium concentrations and organic matter influenced the soil acidity.

The cation exchange capacity is also one of the dominant forms of exchange capacity because most soil colloids have more unsatisfied negative charges than positive charges. Exchange capacity is known as the sum total of exchangeable ions which a soil can adsorb and to describe the ability of a soil to hold ions. Several researchers found out that negative charge derived from the clay minerals affected the cation exchange capacity (Ohta et al., 1993; Sakurai et al., 1998; Tanaka et al., 2007; Arifin et al., 2009). Moreover, Tanaka et al. (2007) reported that the cation exchange capacity was higher compared with that of the effective cation exchange capacity, suggesting the occurrence of some variable negative charges. Moreover, the negative charges from soil organic matter to the cation retention capacity might be small judging from a small difference between cation exchange capacity and effective cation exchange capacity.

2.6 Plant – Soil Relationship with Tropical Rainforests Environment

Tropical rainforests consist of complex ecosystems and richness in species diversity. Forests in Malaysia are divided into several classifications which consist of Lowland Dipterocarp Forest (LDF), Hill Dipterocarp Forest (HDF), Peat Swamp Forest, Mangrove Forest, *Kerangas* Forest (Heath Forest), Montane Ericaceous Forest, Oak Laurel Forest, Forest Limestone, and Forest Quartz Ridges (World Wildlife Fund (WWF), 2011). The diversity of forests may be due to the differences of topography within Malaysia and its climate. Topographically, Peninsular Malaysia is characterised by extensive coastal plains in the east and west, hilly and mountainous region with steep slopes in the central and undulating terrain in other parts of the Peninsular, while Sabah is characterised by the western lowlands, the Crocker Range, the central uplands and the eastern lowlands. Meanwhile in Sarawak, it is characterised by a seaward fringe of peat swamps beyond which the terrain is sharply and frequently dissected with ridges often knife edged.

According to World Wildlife Fund (WWF) (2012), the forests in Malaysia are mostly dominated by trees from the Dipterocarpaceae family which occurs on dry land just above sea level to an altitude of approximately 900 metres. This type of forest can be classified according to altitude into lowland dipterocarp forest (LDF), up to 300 metres above sea level, and hill dipterocarp forest (HDF) found in elevation of between 300 metres and 750 metres above sea level, and the upper dipterocarp forests, from 750 metres to 1,200 metres above sea level. However, in Sarawak both the lowland and hill dipterocarp forests are known as mixed-dipterocarp forest (MDF). Symington (1943) stated that, most of the vegetation covered on lowland dipterocarp forest is mainly from *Shorea* spp., *Dipterocarpus* spp., and *Dryobalanops aromatica*. Whitmore (1984) pointed out that generally soils are acidic in brown podzol soil and peaty gley soil which exist in lower montane zone together with

intermediate zone. Moreover, according to Forest Department of Sarawak (2009), mixed dipterocarp forest which lies in between of lowland and hill dipterocarp forest are usually dominated by valuable timber species such as *Eusideroxylon zwageri*, *Dryobalanops lanceolata*, *Dipterocarpus* spp., and *Anisoptera* spp.

Peat Swamp Forests are a tropical moist forest type. It occurs just beyond the coastline on both east and west coasts of Peninsular Malaysia. Major timber species found in this forest include, *Gonystylus bancanus* and *Durio carinatus*. Mangrove Forests, on the other hand, are found in tidal and estuarine stretches which extending from mud flats to where the saline waters end. Mangrove forests are familiar with its tolerant to extreme salinity condition and the most common tree species are *Rhizophora* and *Avicennia*. *Kerangas* Forest or known as Heath Forest occurs on poor and sandy terrain. The most abundant tree species in *Kerangas* Forest is from Myrtaceae family.

Montane Ericaceous Forest starts in the lower elevations of montane forest (about 1,000-1,200 metres) where the dominance of dipterocarp species ends. These are replaced with highly species of oak such as, *Quercus* and *Lithocarpus* sp. Montane Ericaceous forests do not have giant emergent trees, and their overall height is much lower. The canopy typically is 10-20 metres high. Trees with buttresses usually are absent. Distribution epiphytes like, orchids, ferns, moss, lichen, and liverworts are more abundant in montane forests than in lowland rainforests.

Whitmore (1984) reported that in the upper montane rainforest, there is a wide vegetation of moss that covered the trees as well as the surface of the soils, and it is known as “cloud forest”. These conditions may be due to humid atmosphere occurred as the elevation of the forest increase, the cloud cover become greater thus promotes the humid condition of the forest (Whitmore, 1984). According to Reynders (1964), a pattern of change

in altitude is typically influenced by its parent material and the local topography. A combination of climatic, topographic, and edaphic factors may also have an impact to the ecotone of the forest (Robert, 2000). Carbon to nitrogen (C/N) ratio increases as latitude increases. Low rate of weathering commonly occurred in shallow soil compared to lowland soils that have the capabilities to hold much more cation. Weathering process in lowland soil is not significant to montane forest due to shallow soil (Whitmore, 1984).

The vegetation of tropical mountains exhibits clear changes in structure and physiognomy with increasing elevation. According to Flenley (1979) and Morley (1982), montane vegetation exhibits a more or less uniform reduction in tree species richness with altitude. Nevertheless, the reduction in a number of species occurs at higher elevation are due to decrease in temperature as elevation increases (Harrison et al., 1989).

On the other hand, lower montane forest is slightly lower stature than lowland evergreen rainforest, which is lacking in emergent trees and is generally without big woody climbers, buttresses, and cauliflory, although bole climbers and epiphytes are abundant. The change from lowland to lower montane forest seems largely controlled by temperature as it is normally observed at the elevation where the average minimum temperature drops below 18°C. At this threshold many tree species that are typical of lowland forest are displaced by a floristically different assemblage of montane species. Besides that, a further reduction in the height of trees occurred until up to the upper montane forest and subalpine forest (Robbins, 1998). Nonetheless, Whitmore (1984) postulated that generally there are further decreases in stature and leaf size as it goes in higher altitude. The generalised altitudinal forest formation series in the humid tropics is shown in Figure 2.8.

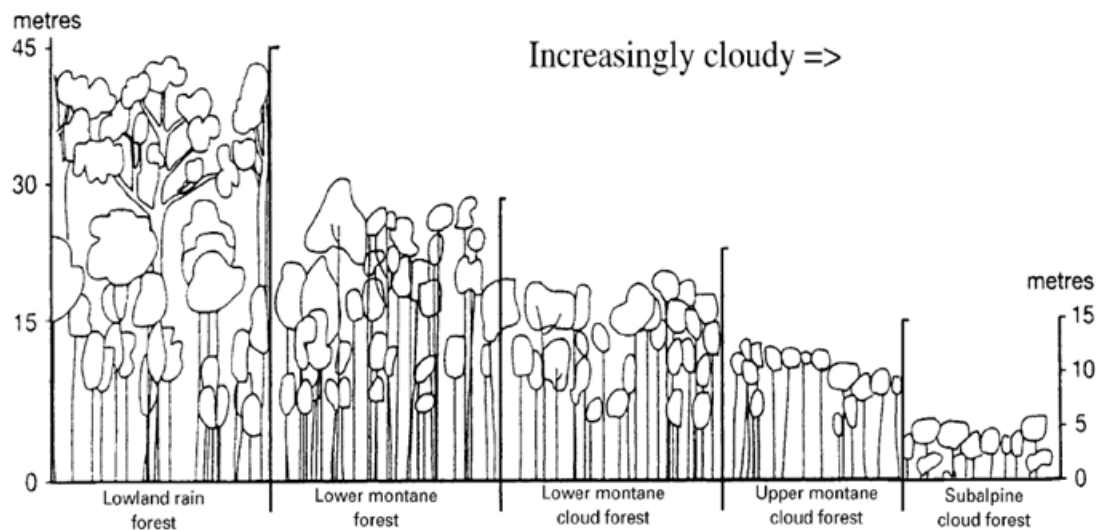


Figure 2.8: Generalised altitudinal forest formation series in the humid tropics.

(Source: Whitmore, 1984)

2.7 *Shorea macrophylla* (de Vriese) P.S. Ashton and Its Potential in Reforestation Activity

2.7.1 General Information on *Shorea macrophylla* (de Vriese) P.S. Ashton in Sarawak

Shorea macrophylla is one of the most important species in Sarawak and has been selected as one of the indigenous species to be planted in the shifting cultivation area or degraded land in Sarawak (Chai, 1998). According to Chai (1998), one of the reasons for selecting this species in the state is probably due to its fast growing rate and also due to the fact that no other indigenous species in the state can compare with the fruits or illipe nuts it produces as well as its long established economic value of the nuts generated as early as 1908 long before the export of timber has started in Sarawak. Ng and Tang (1974) reported that the mean annual increment in diameter at breast height (MAID) of *S. macrophylla* was 2.2 cm which grows well on clay alluvial soil of riparian forest and lower slopes of clay hills below

600 m above sea level. Tan et al. (1987) noted that 3.8% of the 395 *S. macrophylla* in Semengoh Forest Reserve, Sarawak grew at 2.1 cm per annum from 1967 to 1964. Planting of *S. macrophylla* had commenced as early as 1982 (Chai, 1998).

2.7.2 Taxonomic Classification

Shorea macrophylla (de Vriese) P.S. Ashton belongs to the genus (*Shorea*) in the family of Dipterocarpaceae and is an endemic species of Borneo Islands (Wood & Meijer, 1964; Soerinegara & Lemmens, 1993; Newman et al., 1996). The species was first named as *Shorea gysbertsiana* Burck as reported by Wood and Meijer (1964). However, in 1962, Ashton (Wood & Meijer, 1964) argued that a sterile specimen of *Hopea macrophylla* (de Vriese) belongs to *Shorea gysbertsiana*. In the absence of the type specimen of *Hopea macrophylla* at Leiden for confirmation, finally the name *Shorea macrophylla* (de Vriese) P.S. Ashton was adopted as a combination from *Shorea gysbertsiana* and *Hopea macrophylla*. The following are the taxonomic classification from Kingdom to Species of *Shorea macrophylla* (de Vriese) P.S. Ashton as shown below:

Kingdom: Plantae	Sub-class: Dilleniidae
Sub kingdom: Tracheobionta	Order: Theales
Super division: Spermatophyta	Family: Dipterocarpaceae
Division: Magnoliophyta	Genus: Shorea
Class: Magnoliopsida	Species: <i>Shorea macrophylla</i> (de Vriese) P.S. Ashton

2.7.3 Vernacular Names

Engkabang is an Iban name of a tree group consisting of twenty species of a genus *Shorea* in Dipterocarpaceae in Sarawak (Smythies, 1958; Anderson, 1980). Hotta (1992a, 1992b) described as it appears to correspond to a local species group known as *Kawang* in Brunei and *Tengkawang* in Indonesia, though some confusions in identification are recognisable between researchers and between Sarawak and Indonesia. *Shorea macrophylla* has several common names as it is locally known as *engkabang jantung* in Sarawak, *engkebang*, *kawang jantung* (Sabah), *tengkawang hantelok* (Indonesia), *tenkawang buah* and *awang katolok* (Kulip, 1999). It has also been recorded as *engkabang amat*, *engkabang ayer*, *engkabang ringgit* and *abang taha* (Browne, 1955). It is known as Light Red Meranti in English. Translated from Malay, *Jantung* means “heart”, referring to the shape of the winged seeds (Lee, 2013). In France, *Shorea macrophylla* commonly known as *Illipé de Bornéo*, *Noix de tengkawang*, *Noix d' illipé* and *Illipé Tengkawang*.

2.7.4 General Botanical Description and Morphology of the Species

In Malaysia, one of the most common species of trees chosen for reforestation and rehabilitation purpose is the timber trees mainly from Dipterocarpaceae family. *S. macrophylla*, or *Engkabang jantung* as it is commonly known in Sarawak, is a medium to large timber-sized tree of the family Dipterocarpaceae and valued for its oil-bearing fruits and is one of the large-fruited species of illipe nuts. The species has been frequently planted by local de Vriese people for illipe nut production. According to Lee (1981), the species is nominated for one of the promising species for future plantation forestry in Sarawak, and its genetic structure is required to be clarified. It is a member of the red meranti *Shorea* group whereby it produces sawn timber known as *Meranti* or *Seraya* (Anderson, 1980) and is

planted by local peoples for its common utility. Dipterocarpaceae is the most well-known trees family in the tropical forest. This family generally consists of 580 species in 15 genera of palaeotropical distribution, but is found chiefly in Malaysia and Indonesia. The genus *Shorea* consists of 188 species and is widely distributed from Sri Lanka, India, Myanmar through Indochina and Malaysia. In the Mixed Dipterocarp Forests of Sarawak and Brunei, this *Engkabang jantong* tree can attain a height of 50 m tall, 4.0 m in stem girth at breast height, and 2.0 m in buttress height. Specific gravity of stem is in a range between 0.3 and 0.5. The bole, usually with small but long buttresses, branches early, and is frequently bent or leaning. It has large wide spreading crown with big limbs, oblong to hemispherical, open and irregular (Ashton, 1964, 1982).

S. macrophylla has a smooth, brownish-green bark when young, becoming cracked and flaky on old trees. It has a thick canopy with large crown and simple leaves. A young leaf can exceed 30 cm in length, but on average it is about 20 to 25 cm. On the other hand, the width ranges from 7 cm to 10 cm and leaves of seedlings are usually larger than those of the mature trees. The upper surface of the leaf is smooth and slightly leathery on the lower surface. It is elliptic or ovate with a short pointed apex. When the leaf is dry, it is almost black above and reddish brown below. There are approximately 15 pairs of nerves and the leaf stalk is 2 to 3 cm long. *S. macrophylla* is one of the shade tolerant species (Chai, 1998).

Anderson (1975) stated that *S. macrophylla* is a $2n = 14$ chromosomes species. The leaves of *S. macrophylla* are large and this tree exhibits a very fast growth rate, possibly the highest of all *Shorea* species. It is a one of the fastest-growing timber species among the *Shorea* (Wood & Meijer, 1964, Newman et al., 1996) which reaches 50-60 cm in diameter breast height in 20-30 years. According to Appanah and Weinland (1993), this Bornean species with exceptionally fast growth, can achieve mean annual increment (MAI) of basal

area 8.83 m³/ha. Browne (1955), reported that this light red meranti trees in experimental plantations of Peninsular Malaysia have attained an average girth of about 1.5 m in 23 years. In addition, *Engkabang jantong* achieved 48 cm diameter in 23 years at Kepong and in Semengoh, Sarawak plantations, this species attained an annual diameter increment of 1.22 cm. This represents approximately 2 to 3 times higher compared to the natural forest than in both primary and logged forests (Appanah & Weinland, 1993). Halle et al. (1978) described that the architecture of the mature tree of *Shorea* belongs to the Roux's (*Shorea pinanga*) models which includes *Shorea* and *Dipterocarpus* in the Dipterocarpaceae family and other dicotyledonous families. Based from Roux's definition, the tree structure is determined by a monopodial orthotropic (vertical response) trunk meristem which shows continuous growth. The branches are plagiotropic (horizontal response) and inserted continuously.

Apart from the valuable timber, *S. macrophylla* is also the best producer of big nuts, which are large enough to be worth collecting, and is also known as illipe nuts for the illipe nut butter that is characterised by a relatively low melting point similar to human body temperature and is used for food, cosmetics, etc. (Lee et al., 1997). Nuts of this light red meranti yield are rich in fats and used in the manufacture of chocolate industry. The fruit is the principal source of the illipe nut export trade in Sarawak (Meijer, 1969). The wood of this species is one of the lightest in the red meranti group. Browne (1955) stated that the wood is very light and brittle, and is probably the weakest of all red meranti timbers in Sarawak and Brunei. Figure 2.9 shows the bark, fruit and leaf arrangement of *S. macrophylla*.

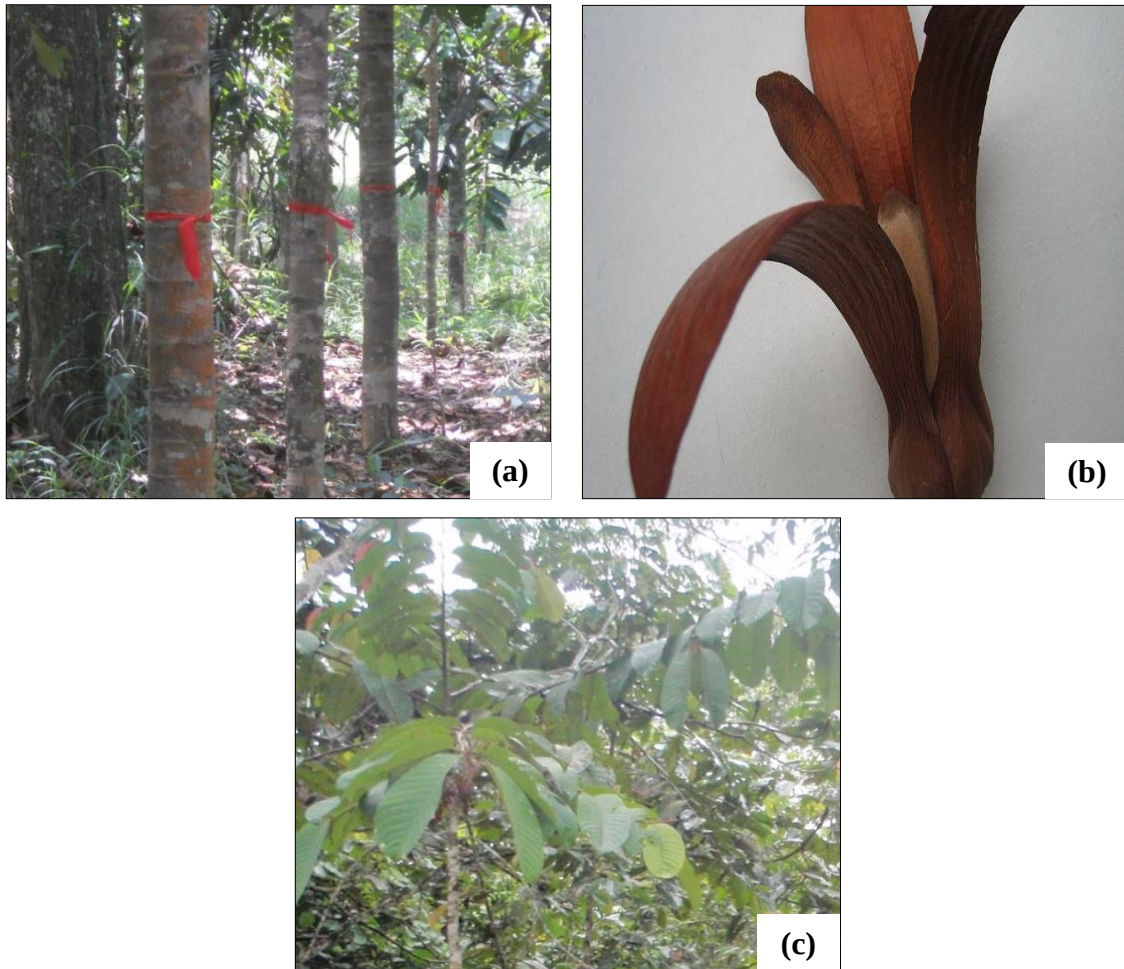


Figure 2.9: (a) The bark of *S. macrophylla* is greyish brown outside and reddish, pink or orange inside. (b) The ovoid nuts of *S. macrophylla* are enclosed by 3 longer and 2 shorter calyx lobes. (c) The leaves of *S. macrophylla* are broadly ovate.

2.7.5 Natural Range Distribution and Habitat

S. macrophylla is endemic to Borneo (Ashton, 1964) and is especially widespread in west and central Sarawak, Kapuas valley, Tidung and Burau. Sim (1978) reported that in Sarawak, these species' habitats are commonly found in Lundu, Bau and Serian areas in the first division; along the rivers and tributaries of Batang Lupar river in second division; Oya and Mukah rivers in the third; Balingian, Kemana and Bintulu rivers in the fourth and Rejang river in the seventh division. Apart from the natural stands in the forest, small plots varying from a few scattered trees to 0.7 hectare for the production of fruits were established next to

the longhouses in the rural areas, especially in the central regions of Sarawak (Chai, 1998). According to Wood and Meijer (1964), in Sabah, this species is widely distributed but only locally common and is unaccountably absent in other locations. Anderson (1975) noted that its distribution was predominantly in north and central Borneo, becoming less frequent towards the east (Sabah, Kalimantan Timur).

S. macrophylla is commonly found in lowland tropical rainforest, and seldom occurs above 600 m in altitude (Ashton, 1964; Wood & Meijer, 1964). Browne (1955) stated that *S. macrophylla* is the most typical large tree of riparian or *emperan* forests in Sarawak. Due to the encroachment of agriculture onto these fertile sites, and because of the rather localised distribution of *emperan* forests in Sarawak, natural stands of *S. macrophylla* are becoming less common. However, due to the importance of the illipe nut, some *S. macrophylla* trees have been preserved and new ones planted for reforestation and rehabilitation purpose.

Engkabang jantong occurs on clay riparian alluvium, where it is locally abundant (Lee et al., 1997). Natural habitat of the species is periodically flooded alluvium and river banks, rare in hillside (Kanzaki et al., 1996). Besides that, the preferred habitat of this species is usually in areas where the soil has higher water retention ability. According to Rasip and Lokmal (1994), this species is confined to damp clay soils near rivers and streams and has less favorable growth in hill sides, ridge tops or upper slopes. However, it seldom occurs on sandy alluvium and is completely absent from peaty alluvium. As usually known, *S. macrophylla* is rarely gregarious and is often scattered at a low density. This canopy species is commonly found in riparian forests and also establishes well in canopy gaps. Regeneration is dense, which react instantly to gaps and the poles reach canopy within a few years. *S. macrophylla* is phototropic, and needs to be carefully conditioned as a young plant. It needs medium shade for conditioning, and in gap conditions it grows with excellent form.

Moreover, it makes an excellent species for line planting into secondary growth (Food and Agricultural Organization, 2009).

2.7.6 Flowering and Fruiting

Engkabang fruit is synonymous with the Iban community living in the interior part of Sarawak. It has petals or about four to five small wings which act as the protector of the fruit. The flower is characterised by its winged fruits with a 5-merous calyx and resembling a badminton shuttlecock (Chai, 1998). One of the interesting features of the fruit is that a matured fruit will rotate before dropping to the ground. The amount of fruits a *S. macrophylla* bears will depend on the maturity of the tree and its crown structure. Flowering usually occurs in September to October and the fruit ripens in the following January and February (Sim, 1978; Appanah & Chan, 1981). Chai (1998) stated that the yield may continue to late March and April in very favourable years. The flowering behaviour of *S. macrophylla* is notoriously unpredictable. There is always some flowering of dipterocarps each year, however, the amount of flowering and consequent seed production is very small. Though, usually it has a pattern of mass fruiting only once in every 2 to 5 years. This phenomenon is known as 'gregarious' or 'general flowering'. According to Burgess (1972), analysis of the phenology data collected from the year 1927 to 1970 showed that gregarious flowering occurs at interval of 2-3 years, with occasional interval up to 5 years. Moreover, Cockburn (1975) has analysed similar data from Sabah and come to the same conclusion. The stimulus triggering for gregarious flowering is not clear, although Burgess (1972) suggested that it is related to periodic water stress and the accumulation of carbohydrates during the dry season in August to October. This species of *Shorea* are pollinated by a wide

variety of animal and insects which include thrips, stingless bees, beetles and moths (Appanah & Chan, 1981).

2.7.7 The Seeds (Illipe Nut)

Seeds of *S. macrophylla* are dispersed by wind with the aid of the long calyx, modified into wing-like structures (Chai, 1998). According to Anderson (1975), the seeds of *S. macrophylla* are recalcitrant and have a very short viability period, usually 2-3 days. Generally, the fruits of the genus *Shorea* vary considerably in appearance. However, those from species of economic importance are generally ovoid and can vary in size considerably within the individual species as well as inter-specifically. For example, the largest specimen seen of a fruit from *S. macrophylla* had a length of 7 cm on the major axis and breadth of 5 cm on the minor axis; in comparison the average size of fruits from this species was 4.5 cm x 3.0 cm and the smallest size of fruits seen from *Shorea seminis* and *Shorea palembanica* was 1.5 cm x 1.0 cm. All possess the persistent five calyx, which is typical of the Dipterocarpaceae, surrounding a thin woody shell which encases the four segmented kernel. It is the kernels of the fruits which are commonly known as illipe nuts. Lee et al. (1997) reported that together with five other *Shorea* spp., the seeds have been known by the foreign traders as illipe nuts. The five other species which produce illipe nuts besides *Engkabang jantong* (*Shorea macrophylla* (De Vr.) Ashton) are *Engkabang asu* (*Shorea palembanica* Miq.), *Engkabang bintang* (*Shorea splendida* (De Vr.) Ashton), *Engkabang gading* (*Shorea hemsleyana* King ex Foxw.), *Engkabang rusa* (*Shorea stenoptera* Burck) and *Engkabang terendak* or *Engkabang tegelam* (*Shorea seminis* (De Vr.) V.S1.). Out of twenty species of *Engkabang* recorded in Sarawak, all these species are now protected by the Sarawak state government under the Wild Life Protection Ordinance 1998, owing to their ethnobotanical

utility (Lee et al.,1997). Other *Shorea* spp. are also the sources of illipe nuts, however, their productions are insignificant. Jantan (1994) stated that Sarawak (Malaysia) and Kalimantan (Indonesia) are the main producers of illipe nuts from Borneo Island.

The value of nuts depends on the size and the oil content of the kernels (Chai, 1998). The seed of *S. macrophylla* has very high oil content (Anderson, 1975; Sim, 1978; Nesaretnam & Ali, 1992) because of its larger size (almost the size of a hen's egg). Ahmed and Sim (1973) as well as Anderson (1975) stated that approximately 28-42 nuts weigh a kilogram and the weight of a single fruit is up to 50 grams with a specific gravity of 0.967.

2.7.8 Soil Requirements for *Shorea macrophylla* (de Vriese) P.S. Ashton

Meijer (1969) described that *Shorea macrophylla* makes its best growth in alluvial riverine soils. In Brunei, the tree is confined to damp clay soils on hillsides by rivers and streams, where it is scattered and rare, and on clay riparian alluvium where it is locally abundant (Ashton, 1964). The information on soil requirements for *S. macrophylla* is still scarce and lacking. However, from the observations of its natural habitat, it is suggested that deep, most alluvial clays or loams are among the ideal soils for the growth of *S. macrophylla* (Butt & Chiew, 1982).

According to Maas et al. (1974), the Department of Agriculture, Sarawak listed that the illipe nut is having similar soil requirements to rubber trees. Suitable qualities are among well to imperfectly drained, sandy loam to clay soils at least 50 cm deep on slopes less than 30°. For most of the *engkabang*, it can tolerate regular, short flooding. *Engkabang* can also be grown on organic type of soils provided that the organic horizon is less than 100 cm thick, the water table lies at a depth greater than 60 cm and the subsoil is fine loam to clay.

Recently, Forest Department of Sarawak has continued to plant *S. macrophylla* in trial plantations at Semengoh, Sabal, Sawai, Gunung Gading, and Niah Forest Reserves as well as in the Oya Road experimental plantation in order to test the adaptability of *S. macrophylla* to be sited in deep alluvial soils subject to short-lived floods or moist lower slopes receiving ground water influx. In terms of fertilisers application, the technique and exact amount of fertilisers to be applied for *S. macrophylla* similarly is not yet available but application has been either broadcast, by hand, over a circle of radius 30-60 cm around the stem, or placed in radial slits either upslope or encircling the stem on level sites.

For the fertiliser application, latest recommendations made by Forest Department of Sarawak was by placing 113 g of double or triple superphosphate in the planting hole, then applying 170 g to 225 g of Nitrophoska Blue (12:12:17:2 + trace elements) 2 to 3 times per year for about 6 years. Lee (1980) reported that fertilisation has not yet stimulated precocious flowering in *S. macrophylla* as it has in *Shorea pinanga*. Though, Anderson (1975) has suggested that fertilisation may, in general, have that effect on most *Shorea* species.

2.7.9 Economic Significance of *Shorea macrophylla* (de Vriese) P.S. Ashton

In terms of economic significance, *S. macrophylla* is an important source of quality wood. For its wide range of applications, it is particularly important for producing plywood, veneer (face and core), hardboard and furniture. Nuts of *Engkabang jantong* yield fats which are used in the manufacture of chocolate, cosmetics, soaps and candles. The oil produced from the fruit is used as cooking oil or massage oil. Moreover, fruits are boiled and eaten with hot rice by the local people. According to Chai (1998), the larger nuts are usually dried for export, and the smaller ones for home consumption. The high melting point of the illipe nut butter makes it solid at room temperature. Apart from that, the Borneo illipe nuts contain

fatty acid and mainly symmetrical mono-unsaturated triglycerides as cocoa butter and are an important source of food to the wildlife in the forests such as wild boar, woodpeckers, foxes, rodent, freshwater fish, squirrel and local reindeer (Wong, 1988; Blicher-Mathiesen, 1994).

2.8 Plant Morphological Attributes that Define Seedling Quality

Seedling quality is a critical component of any successful forest restoration program. Seedling quality refers to physical and genetic characteristics. Physical quality refers to the physical condition of the seedlings as it is raised in the nursery, while genetic quality relates to the genetic characteristics of the source of germplasm (Gregorio et al., 2010). The seedling physical quality can be improved by good practice within the nursery but there is no quick fix to improve the genetic quality of seedlings. Over the past century, the concept of seedling quality has evolved to the point that plant attributes are used to improve seedling nursery culture and to predict seedling survival and growth after outplanting (Grossnickle & MacDonald, 2018).

Plant attributes have been evaluated at the morphological and physiological levels. However, in reality, only a restricted number of attributes are used within operational programs (Mohammed, 1997), since an “ideal operational measure” needs to be rapid, simple, cheap, reliable, non-destructive, quantitative, and diagnostic (Zaerr, 1985). Commonly measured morphological attributes include shoot height, root collar diameter, root systems, and shoot-to-root ratios (Pinto, 2011). According to Takoutsing et al. (2014), these attributes are easy to measure in operational settings, ensuring their use in small-scale nurseries in developing countries and large commercial nurseries in first-world countries (Grossnickle, 2000; South, 2000; Grossnickle & South, 2017). At forest restoration sites, seedling survival and growth after planting are influenced by morphological attributes

because they retain their mark on seedling attributes for extended timeframes (Grossnickle, 2012; Grossnickle & MacDonald, 2018). Greater root collar diameter and size of the root system confer a higher chance of survival and growth, because they limit susceptibility to planting stress by improving water uptake and transport to foliage (Grossnickle & MacDonald, 2018). Interestingly, it was found that root collar diameter was still the best attribute to forecast field growth potential after South (1987) revisited the morphological criteria defined by Wakeley (1954). Several researchers reported that greater height provides a competitive advantage (i.e., access to light) on sites with competing vegetation. However, seedlings with smaller shoot systems or lower shoot-to-root ratios are better adapted when potential site environmental conditions are limiting (e.g., dry soils, high evaporative demand).

Morphological attributes which are commonly used in seedling quality programs to monitor either the process during nursery culture or the product at the end of culture are reported by numerous researchers as shown in Table 2.5. It is significant to emphasise that no single attribute can evaluate seedling quality issues (Mattson, 1997; Puttonen, 1997).

Table 2.5: Morphological attributes commonly used in seedling quality assessment programs to monitor either the process during nursery culture or the product at the end of culture.

Attribute	Application	Monitor the Process	Monitor the Product	References ¹
Bud development	Growth		×	Thompson (1985), Colombo (1986), Templeton (1993)
Dry weight fraction	Lift/ store	×		Colombo (1990), Calmé et al. (1993), Binnie et al. (1994)
Height and diameter	Crop development	×		Wakeley (1954), Cleary et al. (1978), Armson and Sadreika (1979), Tinus and McDonald (1979), Rose et al. (1990), Landis et al. (1995)
Height and diameter	Survival, growth		×	Toumey (1916), Wakeley (1954), Cleary et al. (1978), Armson and Sadreika (1979), Sutton (1979), Chavasse (1980), Schmidt-Vogt (1981), Burdett (1983), Ritchie (1984), Mexal and Landis (1990)
Morphological ratios	Survival, growth		×	Toumey (1916), Wakeley (1954), Timmis (1980), Burdett (1983), Ritchie (1984), Thompson (1985), Puttonen (1989)
Root system	Crop development	×		Wakeley (1954), Cleary (1978), Armson and Sadreika (1979), Rose et al. (1990), Landis et al. (1995), Davis and Jacobs (2005)
Root system	Survival, growth		×	Toumey (1916), Wakeley (1954), Lavender (1976), Schmidt-Vogt (1981), Burdett (1983), Thompson (1985), Kramer and Jose (1986), Glerum (1988), Puttonen (1989)
Shoot and root weight	Survival, growth		×	Wakeley (1954), Thompson (1985)
Shoot system dimensions	Growth		×	Grossnickle (2000), Grossnickle et al. (1991)
Qualitative shoot trait ²	Survival, growth		×	Toumey (1916), Wakeley (1954), Thompson (1985), Haase (2008), Ritchie et al. (2010), Villar-Salvador et al. (2010)
Qualitative root trait ³	Survival, growth		×	Toumey (1916), Wakeley (1954), Thompson (1985), Colombo et al. (2001), Haase (2008), Ritchie et al. (2010), Villar-Salvador et al. (2010)

¹ References are either the initial research conducted on an attribute and/ or citations that initially recognised the attribute for inclusion in seedling quality programs at nurseries; ² Examples: lack of terminal bud, multiple stems, stem curvature; ³ Examples: deformed root, poor plug development.

(Source: Grossnickle & MacDonald, 2018)

CHAPTER 3

DESCRIPTION OF THE STUDY AREA

3.1 General Information about Sarawak, Malaysia

This study was conducted in Borneo Island, Sarawak, Malaysia. Sarawak is the single largest of 13 states in Malaysia and is one of the two Malaysian states located on the island of north-west Borneo. Sarawak or known as the “Land of Hornbill” lies between the northern latitudes 0°50’ and 5°N and eastern longitudes 109°36’ and 115°40’E. Sarawak occupies a total land area of 124,450 km², making up 37.5% of the total area of Malaysia. Sarawak’s tropical rainforest is well known as one of the oldest tropical rainforests with high concentrations of species biodiversity per unit area in the world. According to Bryan et al. (2013), only 3% of land area in Sarawak was covered by intact forests under designated protected areas. Chai (2000) reported that the distribution and extent of Sarawak’s natural vegetation are largely determined by edaphic factors and climate changes due to the altitudinal sequence.

Sarawak has an equatorial tropical humid climate with high average annual precipitation around 2,800-5,300 mm. The mean monthly rainfall is high exceeding 100 mm for all months of the year. It lies within the tropical monsoon belt which is mostly influenced by the Indo-Australian monsoon (Whitmore, 1975). The seasonality of rainfall is associated with the directions of the monsoon seasons; a north-east monsoon and south-west monsoon. During the north-east monsoon (October to February), the rainfall is higher than the average whereas during the south-west monsoon (March to September), the rainfall is relatively lower as compared to the average. The temperature is comparatively stable and uniform except for the two monsoons, with an average daily temperature between 23-24°C in the

morning to 31-32°C in the afternoon. At mid-afternoon, the mean relative humidity ranges from 68-73% throughout the year.

The state of Sarawak can be broadly divided into three physiographic ecoregions, i.e. coastal lowland, central lowland, and interior upland, accounting for 19.6%, 33.3%, and 47.1% of the total land area, respectively (Teng, 2003). The steep lands are covered mainly by the Red-Yellow Podzolic Soils and Skeletal Soils in the Sarawak classification system, corresponding roughly to Paleudults/ Dystrudepts and Udorthents, respectively, according to USDA classification system (Soil Survey Staff, 2014). In terms of general soil physicochemical properties, Sarawak soils are categorised as acidic, shallow, and of poor quality. Jomo et al. (2004) mentioned that the soils of Sarawak are subject to considerable erosion, leaching, and oxidation of soil nutrients, once exposed. Therefore, they pose obstacles to agricultural development and diversification as the widespread clayed, silty, and loamy upper layers are most susceptible to erosion after development operations (Jomo et al., 2004).

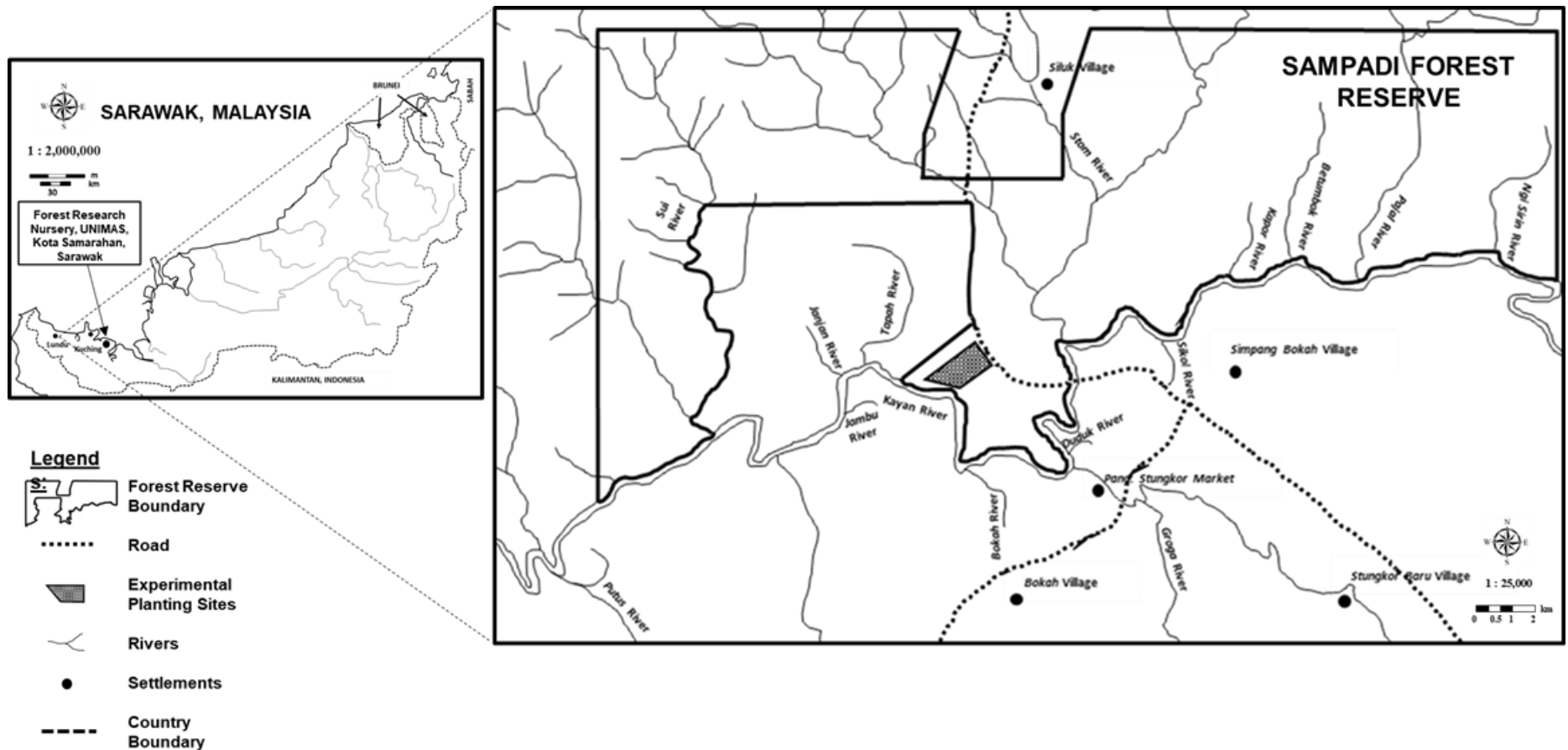
3.2 Study Areas

In this study, data collections were conducted at two main study areas. For Chapter 4, Chapter 5, Chapter 6, and Chapter 8, the experiments were conducted at Sampadi Forest Reserve, Lundu, Sarawak whereas for Chapter 7, the experiment was performed at Universiti Malaysia Sarawak (UNIMAS) Forest Research Nursery, Kota Samarahan, Sarawak. Specifically, the study on the evaluation of soil morphological and physiochemical properties, survivorship, and growth performance, as well as the association between soil fertility and growth performance after enrichment planting of *S. macrophylla* were conducted at the Sampadi Forest Reserve. Meanwhile, the study on the influences of

inorganic and organic fertilisers to morphological quality attributes of *S. macrophylla* seedlings was performed at the Forest Research Nursery of UNIMAS from February 2015 to November 2015. Finally, the study on the effects of initial seedling age on the subsequent outplanting performance of *S. macrophylla* was conducted at Sampadi Forest Reserve from May 2015 to March 2019.

3.2.1 Universiti Malaysia Sarawak (UNIMAS) Forest Research Nursery, Kota Samarahan, Sarawak, Malaysia and Sampadi Forest Reserve, Lundu, Sarawak, Malaysia

The Universiti Malaysia Sarawak (UNIMAS) Forest Research Nursery or known as the greenhouse is located at the East Campus of the university in Kota Samarahan, Sarawak, Malaysia (N01°27'820", E110°27'079") (Figure 3.1). The climate data were collected from the nearest Kuching Airport Station, which is approximately 13.9 km in distance between the nearest climate station to the study site with a consistent climatic record. During the last two years (2015-2016), the study site receives an average of 3,936 mm year⁻¹ of rainfall (Drainage & Irrigation Department, 2017), 27.1°C of monthly average surface air temperature, and 83.8% of monthly average relative humidity (Meteorological Department, 2017). According to the Schmidt-Ferguson classification system (1951), Kota Samarahan region is characterised as zone A with Q (Quotient) of 0.085 with high humidity and covered with vegetation of tropical rainforests. Figure 3.2 illustrates the monthly average of rainfall, surface air temperature, and relative humidity during the last two years (2015-2016) in Kuching, Sarawak. During the last two years from 2015 to 2016, the rainfall distribution in the study site shows that February and November as the month with high rainfall (above 450



(Source: Perumal et al., 2017a, 2017b; Department of Agriculture, Sarawak, 2018; Mohamad Jaffar et al., 2018a)

Figure 3.1: Map/ location of the study area: Forest research nursery of Universiti Malaysia Sarawak (UNIMAS), Kota Samarahan, Sarawak and Sampadi Forest Reserve, Lundu, Sarawak experimental planting sites.

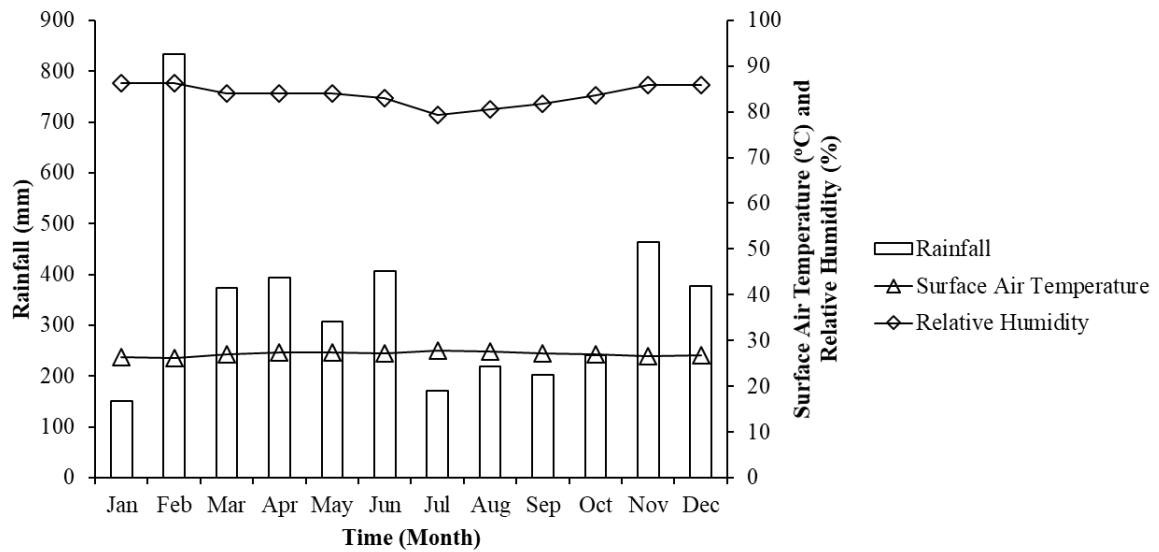


Figure 3.2: Average monthly rainfall, surface air temperature, and relative humidity during last two years (2015-2016) in Kuching, Sarawak, East Malaysia (Drainage & Irrigation Department, 2017; Meteorological Department, 2017).

mm month⁻¹) as presented in Figure 3.2. February is the wettest month (834.3 mm month⁻¹) and the driest month is in January (151.5 mm month⁻¹).

Sampadi Forest Reserve, Lundu, Sarawak, East Malaysia (N01°34'13", E109°53'12") is located near to Bau-Lundu road and is about 72 km southwest of Kuching City (Figure 3.1). The area covers approximately 5,163 hectares with an average elevation of 87 m above sea level. The topography at the study site is of the low undulating type. Sampadi Forest Reserve has a humid subtropical seasonal climate and wet forest biozone (no dry season) with all months receiving on average more than 100 mm of precipitation (Vincent & Davies, 2003). The climate data are collected from Lundu Station, which is approximately 46.9 km in distance between the nearest climate station to the study site with consistent climatic records. The study site receives an average of 3,361.4 mm year⁻¹ of rainfall during the last 22 years from the year 1995 to the year 2016 (Drainage & Irrigation Department, 2017), 26.3°C of monthly surface air temperature, and 84.4% of monthly

relative humidity from year the 2010 to the year 2016 (Meteorological Department, 2017). Figure 3.3 presents the average monthly rainfall, surface air temperature, and relative humidity in terms of the month during the last 7 to 22 years in Lundu, Sarawak. Based on Figure 3.3, the rainfall distribution in Lundu area shows the months of December to February as the period of high rainfall (above 400 mm month⁻¹) during the last 22 years (1995-2016). The wettest month is January (748.1 mm month⁻¹) and the driest month is May (125.7 mm month⁻¹). In the early hours of the morning, the average annual surface air temperature in the area ranges between 21.5°C (70.7°F) and during mid-afternoon, it rises to around 27.7°C (81.9°F) with little monthly variation (Meteorological Department, 2017). Based on the USDA-NRCS classification system, the soils in Sampadi Forest Reserve corresponds to Typic Paleaquults of Soil Taxonomy (Teng, 2004; Soil Survey Staff, 2014; Perumal et al., 2015).

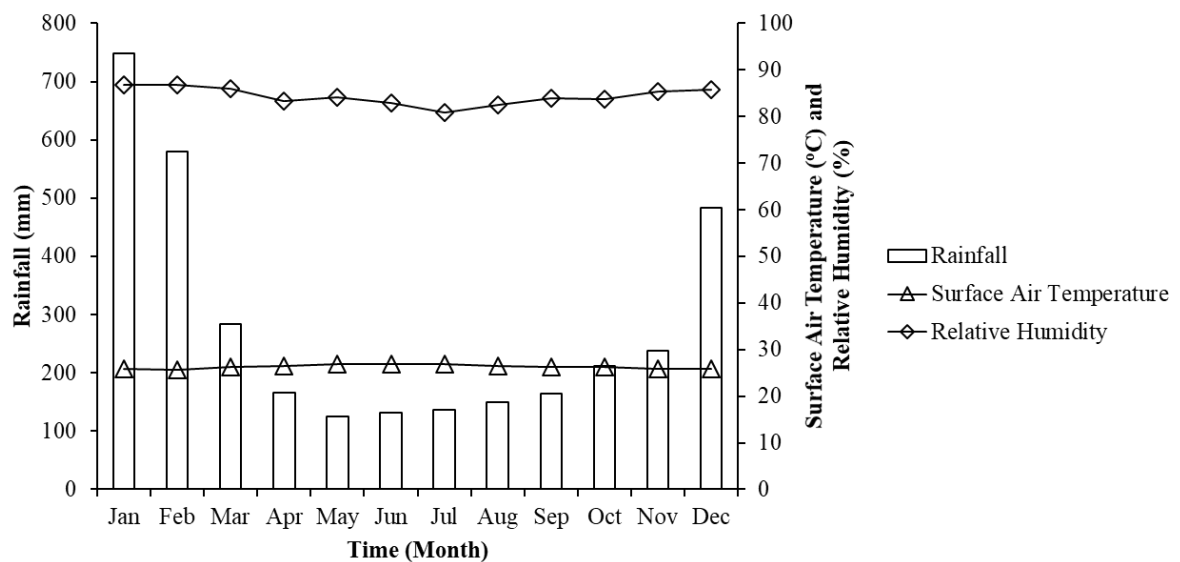


Figure 3.3: Average monthly rainfall (1995-2016), surface air temperature, and relative humidity (2010-2016) in Sampadi Forest Reserve, Lundu, Sarawak, Malaysia (Drainage & Irrigation Department, 2017; Meteorological Department, 2017).

3.3 General Land Use History and Vegetation of Sampadi Forest Reserve, Lundu, Sarawak, Malaysia

The Sampadi Forest Reserve, Lundu, Sarawak comprised predominantly of Mixed Dipterocarp Forest (MDF) and followed by *Kerangas* Forest that had been logged over with some riparian forests found along the main rivers or streams of Batang Kayan (Perumal et al., 2017b). The existing MDF within the research area had been logged in the past 40 years (since the year 1970-1980s) and most of the forests have lost their form and structure. The upper storey of the MDF was represented by relic stands of large trees between 30 and 35m tall and the diameter between 60 and 90 cm. The dominant emergents were *Meranti*, *Lun*, and *Selangan batu* (*Shorea* sp.), *Keruing* (*Dipterocarpus* sp.), *Menggris* (*Koompassia malaccensis*), *Tapang* (*Koompassia excelsa*), *Tampar hantu* (*Sindora* spp.), and *Geronggang* (*Cratoxylum arborescens*). The midstorey was dominated by sparse clusters of smaller trees attaining heights of 15-25 m and diameter of 30-50 cm such as *Empenit* (*Lithocarpus* sp.), *Kayu massam* (*Aporosa* sp.), *Kayu malam* (*Diospyros* sp.), and *Ubah* (*Eugenia* sp.). The lower storey was occupied by dense thickets of small trees and regeneration of larger species. The presence of skid trail and the logging gaps creates dense colonization by woody and nonwoody pioneer tree species. Woody species are represented by *Benuah* (*Macaranga* sp.), *Kelampayan* (*Neolamarckia cadamba*), *Kayu ara* (*Ficus* sp.), *Sabar besi* (*Callicarpa* sp.), and *Buan* or *Simpur* (*Dillenia suffruticosa*) and nonwoody species are represented by *Paku kelindang* (*Blechnum orientale*), *wild ginger* (*Alpinia* sp., *Amomum* sp., and *Costus* sp.), and *Daun long* (*Phrynium* sp.).

Pockets of *Kerangas* forest remained generally undisturbed due to the presence of very poor podzolised soils. Among the tree species typical of this forest were *Somah* (*Ploiarium alternifolium*) and *Geronggang biabas* (*Cratoxylum formosum*) which were

small in diameter and rarely attain the height of eight meters. The area surrounding the Sampadi Forest Reserve has a long history of human habitation. The riparian forest along the major rivers or streams had lost their original forms and structure by shifting agriculture or past logging activities (Forest Department of Sarawak, 1999). A significant portion of the shifting agriculture areas nearby the Sampadi Forest Reserve had been converted to oil palm estates under the Sarawak Land Consolidation and Rehabilitation Authority (SALCRA's) land development program and also to forest plantations by private companies in the last few decades (Forest Department of Sarawak, 1999).

The reforestation sites were established under secondary forests (Perumal et al., 2015; 2017a, 2017b) and based on the *in-situ* observation, among the common pioneer trees (genera) found during site surveys include *Aleurites* (Euphorbiaceae), *Amomum* (Zingiberaceae), *Cratoxylum* (Clusiaceae), *Dillenia* (Dilleniaceae), *Elaeocarpus* (Elaeocarpaceae), *Ficus* (Moraceae), *Hopea* (Dipterocarpaceae), *Ilex* (Aquifoliaceae), *Lithocarpus* (Fagaceae), *Norrisia* (Loganiaceae), *Pentace* (Tiliaceae), *Pentaspadon* (Anacardiaceae), *Sarcotheca* (Oxalidaceae), and *Vitex* (Verbenaceae) (Mohamad Jaffar et al., 2018a). The planted species in the study area were mainly from Dipterocarpaceae family such as *Engkabang jantung* (*Shorea macrophylla*), *Meranti sarang punai* (*Shorea parvifolia*), *Selangan batu* (*Shorea falcifera*), *Kapur bukit* (*Dryobalanops beccarii*), and *Bintangor bukit* (*Calophyllum alboramulum*). Such secondary forests have little commercial value as they are kept in this “forest fallow” state by the local farmers in the region who use this land mainly for hill paddy cultivation. It was also observed that some patches of lands along the Bau-Lundu roads and rivers or streams near villages had been cleared for agricultural purposes. Hence, it seemed that these local people have encroached into the Sampadi Forest Reserve.

In the year 2009, Forest Department of Sarawak reported that Sampadi Forest Reserve was among the area allocated for reforestation activities of indigenous species. In addition, Sampadi Forest Reserve was chosen and involved in Oita-Sarawak Friendship Forest Project whereby, this project gathers participants including students and teachers from the Mie Agriculture High School since the year 1996 till the year 2000 as to conduct reforestation activities with the local community. In the year 1996, 1.6 hectares were allocated and planted with *S. macrophylla* while in the year 1997 and 1998, 1.1 hectares and 1.2 hectares, respectively were planted. Besides, another 1.3 hectares were planted in August 1999 (Forest Department of Sarawak, 2009). The main objective of conducting such reforestation activity is for the purpose of conservation and rehabilitating the forest resources in Sarawak. Previously, the landscapes of Sampadi Forest Reserve were mostly planted with *Acacia mangium* plantation for the purpose of supplying materials for pulp and paper industry. However, due to poor management and disease attack in the plantation area, some patches within the forest reserve were allocated for Friendship Forest Project. Participation from several international agencies from abroad was initiated in this area as to enrich the areas that had been deforested by forest fires as well as from shifting cultivation into mature tropical forests through reforestation of this indigenous tree species, *S. macrophylla*.

Under the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, *S. macrophylla* or known as Light Red Meranti tree species is classified as Vulnerable which if without proper conservation, could lead to its extinction in the tropical rainforest. Thus, in Sarawak, such reforestation efforts are vital and have been conducted for the purpose of rehabilitating the degraded forestland that has been subjected to logging followed by shifting cultivation (Lee & Lai, 1981). Furthermore, it helps to restore the soil fertility in degraded land and maintain the supply of timber production continuously.

CHAPTER 4

**PRELIMINARY EVALUATION ON THE SOIL MORPHOLOGICAL AND
PHYSICOCHEMICAL PROPERTIES AFTER ENRICHMENT PLANTING OF
Shorea macrophylla (DE VRIESE) P.S. ASHTON IN SAMPADI FOREST
RESERVE, SARAWAK, MALAYSIA**

4.1 Introduction

Tropical rainforests of Malaysia are considered as the richest and one of the most complex ecosystems in the world in terms of structure and species diversity existing among the earth ecosystems (Whitmore, 1998; FAO, 2001). According to Shukla et al. (1990), tropical rainforests have an outstanding prominent role and main influence in ameliorating and maintaining global climate change by reducing the accumulation of greenhouse gases. Although occupying only 6% of the earth's land surface, over half of the planet's life forms are found in tropical rainforests (Wilson, 1988). Tropical rainforests not only sustain biodiversity but provide homes to indigenous peoples, pharmacopeias of natural products, and provide crucial ecosystem services, such as flood amelioration and soil conservation.

Despite the multi-functional roles and richness, tropical rainforests are fragile habitats and are being destroyed rapidly at unprecedented rates approximately at an average of 96 000 hectares per year between 1990 and 2010 due to various disturbances (FAO, 2014). Commercial logging activities for timber resources, shifting cultivation, urbanization industry, natural disturbances like landslide and other forms of encroachment are all principal causes of deforestation in tropical regions. Such disturbances have led to damage in soil resources to a degree which delays the establishment of new succession forest after abandonment (Geist & Lambin, 2002; ITTO, 2002). Juo & Franzluebber (2003) and

Sanchez et al. (2003), stated that most soils in the tropical regions are infertile, and once the natural forest has been cleared, nutrients can be rapidly lost consequently leading to longer forest recovery time. Thus, widespread of deforestation is creating a landscape in which mature tropical forests are island within an area comprising of various type of successional vegetation. Degradation in tropical rainforests beyond a threshold and rehabilitation of the forests are critical subject for world foresters, pedologists, and ecologists. Nonetheless, Montagnini et al. (1997) stated that the conversion of forested areas to non-forest lands such as to agricultural land has resulted in the permanent reduction of indigenous species including timber species such as dipterocarp species from the Dipterocarpaceae family.

Information on the soil characteristics and morphological properties on a given land can be determined by observing the soil profile development at various depths of the soil. Generally, soil morphological properties deal with the form and arrangement of soil features and can be observed at both field survey and laboratory analysis. In the field, *in-situ* observation, description, and interpretation of the soil within various soil horizons can portray various soil attributes such as soil name, structure, parent materials, erosion, ground water, compaction, consistency, and drainage of soils. Nonetheless, field observation on the soil morphological properties can sometimes depict the land use history of the soil observed. Moreover, although the performance of tree growth does reflect the soil characteristics, it is still insufficient to describe soil properties in general given that soil development after land use changes may vary widely depending on the soil heterogeneity as well as the existing environment.

Various previous studies have been conducted on natural forests and its dynamics but still less attention has been paid on the secondary forest succession due to its long-term run and difficulties to predict its outcome (Wasli et al., 2009; Zaidey et al., 2010). However,

most of the previous studies have emphasised the growth performance of planted species along with the planting technique with less attention to soil morphological and physicochemical properties under reforestation area. According to the study by Arifin et al. (2008) and Zaidey et al. (2010) in Peninsular Malaysia, empirical data on soil properties of rehabilitated degraded forestland planted with dipterocarp species and non-dipterocarp species is still limited. The rehabilitation of the degraded forest ecosystems requires well-understanding of the soil conditions (Ohta, 1990; Ohta et al., 2000). Moreover, Ishizuka et al. (2000) reported that information about the soil properties under degraded vegetation is rather limited, although several studies on the soil properties of tropical rainforests in Sarawak, Malaysia, have been conducted (Beckett & Hopkinson, 1961; Wood & Beckett, 1961; Ishizuka et al., 1998). Hence, the objective of this study was to assess the current status of the soils morphological and physicochemical properties of the planted forests under reforestation in comparison to an adjacent secondary forest located at Sampadi Forest Reserve, Lundu, Sarawak, Malaysia.

4.2 Materials and Methods

4.2.1 Description of Study Sites

This study was conducted at Japan-Sarawak Friendship Forest reforestation area at Sampadi Forest Reserve, Lundu, Sarawak (N01°34'13''E109°53'12'') which is located about 72 km from southwest of Kuching City. The detail information on the topography, climatic, and soils in Sampadi Forest Reserve was mentioned in Chapter 3.

Prior to the plantation establishment, this area has been under different kinds of land use activities which, in one way or another, affected the edaphic condition of the area. Since the year 1996, Forest Department of Sarawak, along with various international agencies

had initiated a reforestation program by planting various types of dipterocarp seedlings (mainly of Dipterocarpaceae family) such as *Engkabang jantong* (*Shorea macrophylla*), *Kapur bukit* (*Dryobalanops beccarii*), *Selangan batu* (*Shorea falcifera*), *Meranti sarang punai* (*Shorea parvifolia*), and *Bintangor bukit* (*Calophyllum alboramulum*) in the study area. The reforestation sites were established under the secondary forests where all tree seedlings were planted under line planting technique with lines cut 5 m apart and trees planted at 5 m interval along the lines. Preparation and maintenance of planting lines were conducted by the manual slashing of the undergrowth with the bush knife along the planting line. Large pioneer species were left uncut when preparing the planting lines. The occurrence of heavy floods which happened almost every year in Sampadi Forest Reserve had contributed to water retention at the study sites.

4.2.2 Methods for Soil Profile Description

A soil profile is a vertical section through different layers of soil whereby the soil itself should be considered as something that has volume and variability in three dimensions (Schaetzl & Anderson, 2005). In order to clarify soil morphological and physicochemical properties in greater detail, a soil pit with a depth of approximately 70 cm and 1.5 m width was manually dug at the centre of each study sites. For this purpose, a study plot with a size of 75 m x 50 m that consisted of 150 planted *S. macrophylla* trees was established within each studied sites. Abbreviation was coded to represent the studied plots; planted with *S. macrophylla* in the year 1996; SM96, 1997; SM97, 1998; SM98 and 1999; SM99). Soil profile descriptions were conducted adopting the standard procedures by the International Soil Science Society (ISSS) (NRCS, 2002). For the typical soil profile (master horizon), the soil profile was described starting from the top of the profile and the characteristics of the

soil moving towards the bottom of the profile were observed. Characteristics such as colour, texture, consistency, structure, rock fragments, and roots were distinguished. Soil colour was determined by referring to the Munsell Soil Colour chart whereas the texture was determined by “feel method” in the field. Soil hardness (compaction) was measured and examined at every horizon in each study sites by using the Yamanaka-type push cone penetrometer. Soil samples were collected at each horizons depth of the soil profile for soil physicochemical analyses.

4.2.3 Methods for Soil Physicochemical Analyses

The collected soil samples were air-dried for a week, crushed, homogenised, and passed through a 2 mm mesh-sieve before the soil physicochemical analyses were conducted. All plant materials such as fine roots, twigs, and leaves were removed carefully. As for the soil physical analysis, particle size distribution was determined using the pipette method (Gee & Bauder, 1986). Soil bulk density was determined on the undisturbed samples, collected at each soil horizon depth using a 100-cc core sampler with the ratio of the dry mass of soil to the bulk volume of a soil core. Soil pH (H₂O) was measured in distilled water in soil to solution ratio of 1:5 by the glass electrode method (denoted as pH_w). Electrical conductivity (EC) of soil was measured using the supernatant solution after reciprocal shaking for 1 hour at the soil to water ratio of 1:5 and examined using conductivity meter (Eutech Instruments-Cyberscan Con 11). The filtrate from the pH (KCl) measurement was used for soil exchangeable Al analysis. Exchange acidity (Al + H) was determined using the titration method with 0.01M NaOH and the content of the exchangeable Al with 0.01M HCl (Sumner & Stewart, 1992). Total Carbon (T-C) content in soil was determined using the loss on ignition method (McKeague, 1976; Banning et al., 2008). In addition, the soil Total Nitrogen

(T-N) content was determined by Kjeldahl acid digestion method (Bremner and Mulvaney, 1982). The contents of soil exchangeable bases (Ca, Mg, K, and Na) and soil cation exchange capacity (CEC) was measured three times of successive extraction using 1M ammonium acetate, NH₄-OAc adjusted to pH 7.0 and 10% NaCl, respectively, in soil to solution ratio of 1:5. The contents of soil exchangeable bases were determined by atomic absorption spectrophotometry (AAS) (Thermo Scientific, ICE Series 3500) for Ca, Mg, K, and Na. Steam distillation and titration methods were used to determine the cation exchange capacity of the soil. Available phosphorus (available P) content in soil was quantified by the Bray II method in soil to extractant ratio of 1:20 (Bray & Kurtz, 1945; Kuo, 1996) with UV-Vis Spectrophotometer at a wavelength of 710 nm (JASCO V-630). All soil physicochemical analyses were conducted at the Laboratory of Environmental Soil Science, Faculty of Resource Science and Technology, Universiti Malaysia Sarawak (UNIMAS).

4.3 Results and Discussion

4.3.1 Soil Morphological Properties under Various Stand Ages and Secondary Forest at Sampadi Reforestation Area

In this study, the summary of all descriptions and interpretations of soil profiles as well as the view of the observed representative soil profiles are shown in Figure 4.1 and Table 4.1, respectively. Based on the *in-situ* observations during field sampling, the area consisted of existing vegetation which derived after the previous land use was dominated by several woody pioneer tree species and brush species such as *Benuah* (*Macaranga* spp.), *Buan* or *Simpur* (*Dillenia suffructicosa*) and *Kayu Ara* (*Ficus* spp.).

Soil profiles in all study sites showed the existence of sandy, clayey, silty, and loamy texture in the horizons. Thus, according to the Sarawak Soil Classification Systems, the

occurrence of Bako series, which derived from sandy residual parent material as a dominant unit in association with Saratok series that have a coarse loamy or coarse silty particle size were evident in the study area (Andriesse, 1972). Under the Bako series, it is known as Podzols and can be found typically on nearly flat ridges tops or dip slopes such as the topography of lowland and the low undulating hill of Sampadi Forest Reserve. Although no mottling was observed in all horizons of all profiles, one of the significant features of Bako series was the appearance of well-cemented spodic horizon which represents a subsurface horizon in which alluvial organic matter precipitated.

Our results showed that the depth of O horizon in the reforestation areas (SM96, SM97, SM98, SM99) were similar ranging from 1-3 cm as compared to the secondary forest soils which consisted of 4 cm thick of O horizon layer. This slight difference between both areas (reforestation area and secondary forest) leads to the possibility that there were other plots in the secondary forest which might have the depth of O horizon that was more than in the reforestation area. The thin O layer at the reforestation sites was due to the supply of raw materials since the trees were considered as in immature stage (from 15 years old to 18 years old) in comparison to a continuous supply of organic matter from mature vegetation in the secondary forest. This O horizon was the layer where litterfall from the *S. macrophylla* and other pioneer tree species accumulate and cover the topsoil. Decomposition occurs reflects the activity of decomposer that soon returns nutrient back to the soil. Level of soil fertility can be indicated as it forms a layer which regulates the access of soil in getting enough requirements as rainfall and sunlight to maintain its form and structure.

Nonetheless, the soil colour at A horizon of reforestation areas (SM96, SM97, SM98, and SM99) did not differ much as the colour of the soil was within the range of 10YR5/4 to 10YR5/6 which were from yellowish brown to brownish yellow. The accumulation level of

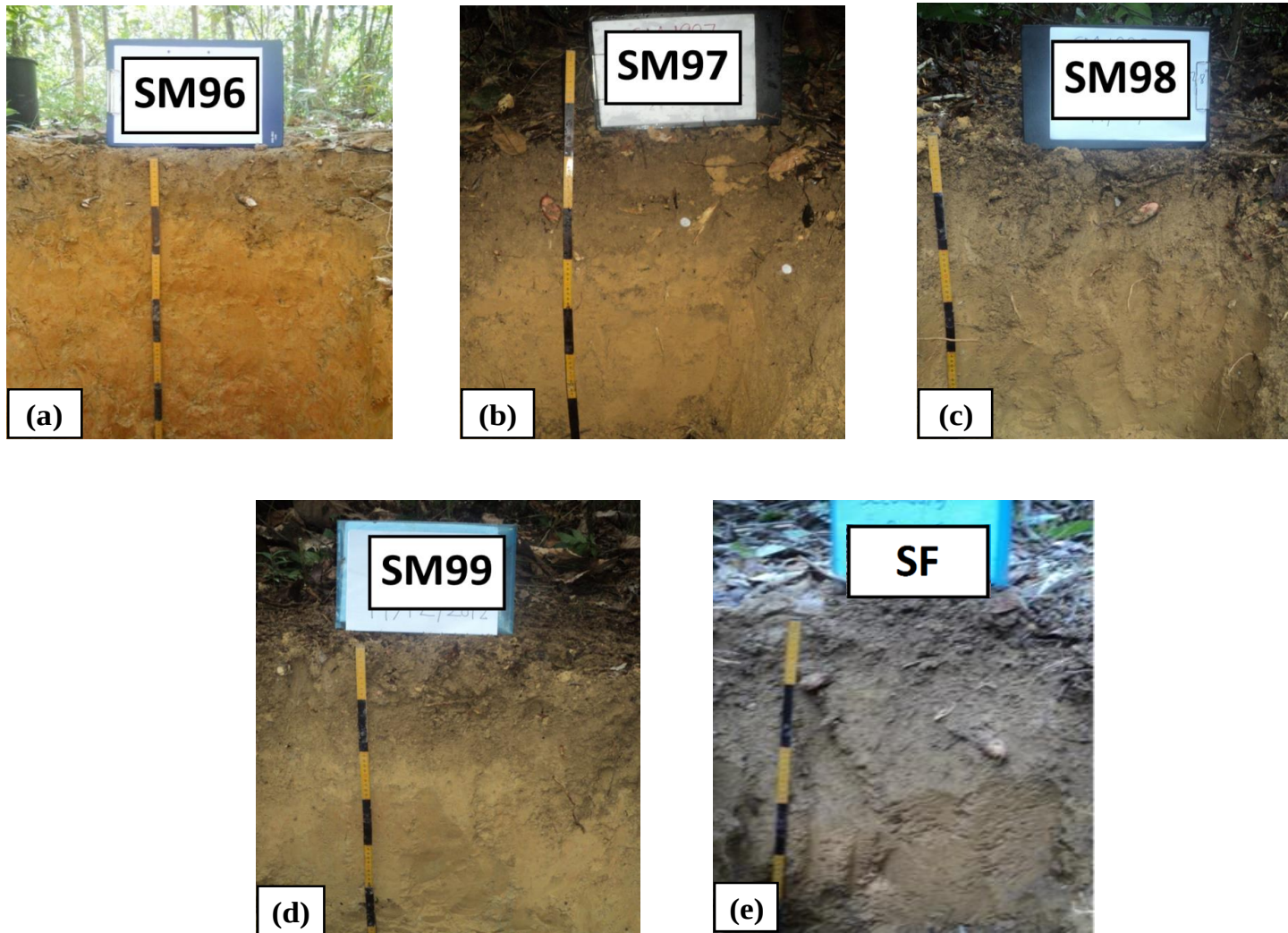


Figure 4.1: Image of soil pit for profile description in the study sites: (a) soil profile for SM96 site; (b) soil profile for SM97 site; (c) soil profile for SM98 site; (d) soil profile for SM99 site; (e) soil profile for SF site.

Table 4.1: Summary of morphological properties of the soils in Sampadi Forest Reserve.

Plot	Horizon	Depth (cm)	Colour	Field Texture ^{a)}	Structure ^{b)}	Consistency ^{c)}	Roots ^{d)}	Boundary ^{e)}	Rock Fragment ^{f)}	Mottling ^{g)}	Hardness (mm) ^{h)}
SM96	(N01°30'15.0", E109°55'00.3"; 11°)										
	O	0-3	Litterfall								
	A	3-13	10YR5/6	SCL-CL	2/m/sbk	ss/p	vf-me/co	gw	co/sa/fg	n	17
	AB	13-30	10YR6/8	SCL-CL	2/m/sbk	ss/sp	f/fe	gw	co/sa/fg	n	21
	B1	30-52	10YR7/6	CL	3/c/sbk	s/p	vf/fe	dw	fe/sa/fg	n	22
	B2	52-70	10YR6/4	SCL	3/c/sbk	s/vp	vf/fe	dw	fe/sa/fg	n	29
SM97	(N01°30'12.0", E100°54'56.0"; 7°)										
	O	0-3	Litterfall								
	A	3-12	10YR5/4	CL	2/m/sbk	s/p	f/c	ds	n	n	14
	AB	12-21	10YR6/4	C	2/m/sbk	s/vp	f/ma	gw	n	n	16
	B	21-70	10YR5/6	C	3/m/sbk	vs/vp	vf/c	cs	n	n	18
SM98	(N01°30'12.1", E109°54'54.8"; 9°)										
	O	0-3	Litterfall								
	A	3-12	10YR5/4	LS	2/m/gr	ss/p	f-me/ma	cw	n	n	15
	AB	12-25	10YR5/6	SL	2/m/sbk	s/p	f/c-me	gw	n	n	18
	B1	25-46	10YR6/8	SiCL	2/m/sbk	s/vp	vf-f/fe	gw	n	n	20
	B2	46-70	10YR6/6	CL	2/m/sbk	vs/vp	vf/fe	dw	n	n	21
SM99	(N01°30'12.1", E109°52'54.3"; 12°)										
	O	0-1	Litterfall								
	A	1-20	10YR5/6	LS	2/m/gr	s/p	f-me/ma	cw	n	n	14
	B1	20-48	10YR7/4	L	2/m/sbk	s/vp	f-vf/fe	dw	n	n	18
	B2	48-70	10YR6/4	SiCL	2/m-s/sbk	vs/vp	n	dw	n	n	19
SF	(N01°30'26.2", E109°58'56.7"; 18°)										
	O	0-4	Litterfall								
	A	4-21	10YR5/6	CL	2/m/gr	ss/sp	f/ma	cw	n	n	14
	AB	21-33	10YR6/4	C	2/m/sbk	s/p	f-vf/fe	dw	n	n	15
	B	33-70	10YR6/8	C	2/m/sbk	vs/vp	n	aw	n	n	20

Abbreviations: ^{a)} Texture: SCL: Sandy Clay Loam, CL: Clay Loam, C: Clay, LS: Loamy Sand, SL: Sandy Loam, SiCL: Silty Clay Loam, L: Loam, C: Clay; ^{b)} Grade: 1: weak, 2: moderate, 3: strong, Type: sbk: subangular blocky, gr: granular, Size: m: medium; ^{c)} Consistency: ss: slightly sticky, s: sticky, vs: very sticky, sp: slightly plastic, p: plastic, vp: very plastic; ^{d)} Root size and abundant: vf: very fine, f: fine, me: medium, c: coarse, n: none, vfe: very few, fe: few, co: common; ^{e)} Boundary: a: abrupt, c: clear, g: gradual, d: diffuse, w: wavy, s: smooth; ^{f)} Rock abundant and size: fe: few, co: common, n: none, Shape: sa: subangular, fg: fine gravel; ^{g)} Mottling: n:none; ^{h)} Hardness was measured using a Yamanaka-Push Cone type penetrometer. Value in parentheses refers to GPS reading and slope.

organic matter from the vegetation, as well as density of below-ground biomass in an artificial forest, promote the higher activity of soil microorganism, which leads to high decomposition rate of organic material in the A horizon. In addition, it should be noted that high mineralisation of organic matter at subsoil layer could also lead to high accumulation of organic matter or humus. Similar findings on the accumulation of organic matter in the top soil had been reported by Ishizuka et al. (1998, 2000). Moreover, Hattori et al. (2005) found that the accumulation of organic materials was higher in the surface horizon at remnant forest than other degraded lands in Sarawak, Malaysia.

On the other hand, relative similarities among other morphological properties at this A horizon, such as soil consistence, and structure, as well as the soil roots, were observed in all soil profiles, with the soil texture ranged from sandy clay loam to loamy sand which allows the penetration of roots around 5-10% and absorption of water to maintain soil moisture. Fine roots were observed in the uppermost layer of the soils across the study areas to the deeper part of the solum, except at the lower part of soil at SM99 and SF sites. This was due to the moderate grade of soil structures and friable consistency, resulting from the sandy clay loam to loamy sand texture in all the sites. Even though differences were observed in term of the soil hardness between all study sites, the soil hardness, especially in SM96, depicted the highest in value as compared to other study sites. Based on the preliminary assessment from previous study conducted by Perumal (2012) reported that it was not a limiting factor for the growth of *S. macrophylla* in SM96 since fine roots were able to penetrate the deeper part of the soil which in a way reflects to the assumption that soil compaction might not have occurred in the present study. Thus, the A horizon properties ensure the successful growth of trees as it serves an ideal depth tandem with the ability of roots to penetrate through the soil in order to get water and nutrients. Meanwhile, there were

no rock fragment and mottling observed at each horizon in all soil profiles except, rock fragment in SM96 site.

4.3.2 Physicochemical Properties of the Soil Profile under Various Stand Ages and Secondary Forest in the Study Area

The physicochemical properties of the soils from soil profiles under various stand ages and secondary forest are shown in Table 4.2. In general, soil pH value increases with depth from the surface to 70 cm for all the soil profiles at the reforestation area and secondary forest as shown in Figure 4.2. The value of acidity decreased with depth, resulting in a higher pH (H_2O). This suggests that the acidification process tend to be higher in the surface horizon than the subsoil. Kadir et al. (2001) reported that the high acidity in the surface soil was associated with hydrolysis of Al, which was released under strongly leaching conditions and which subsequently lower the soil pH and caused toxicity. The acidity occurring in the forest soil was due to the presence of Al^{3+} and H^+ . According to Zaidey et al. (2010), the increase of pH with increasing depth may be related to the contents of Fe and Al oxides, while the content of organic matter exhibit high and low pH values. Lines (2004) reported that the rate of decomposition of organic matter depends on the soil's pH.

Table 4.2: Physicochemical properties of the soils under various stand ages and secondary forest.

Plot	Depth	Horizon	pH (H ₂ O)	EC	T-C	T-N	C/N	CEC	Exch. Ca	Exch. Mg	Exch. K	Sum of Bases	Exch. Al	ECEC ⁽¹⁾	Base Sat. ⁽²⁾	Al Sat. ⁽³⁾	Av. P	Clay	Sand	BD
	(cm)			($\mu\text{s cm}^{-1}$)	(g kg ⁻¹)		ratio				($\text{cmol}_c \text{ kg}^{-1}$)				(%)		(mg P kg ⁻¹)	(%)		(g mL ⁻¹)
SM96	3 - 13	A	5.10	33.7	46.1	2.92	15.80	8.4	0.64	0.27	0.26	1.69	1.10	2.79	20.1	39.5	5.4	39.6	38.9	1.00
	13 - 30	AB	5.22	15.5	30.8	1.73	17.78	7.8	0.06	0.07	0.17	0.79	1.33	2.11	10.1	62.7	1.4	46.0	33.8	1.32
	30 - 52	B1	5.43	7.5	18.4	0.84	21.90	4.8	0.02	0.02	0.14	0.65	1.10	1.75	13.6	62.7	0.7	34.4	54.5	1.51
	52 - 70	B2	5.66	6.0	11.0	0.56	19.60	3.6	0.02	0.02	0.03	0.57	0.65	1.22	15.9	53.2	0.0	27.9	61.7	1.64
SM97	3 - 12	A	4.27	59.0	41.1	2.48	16.59	13.3	0.62	0.25	0.11	1.18	1.18	2.35	8.9	50.0	5.9	33.5	43.7	0.99
	12 - 21	AB	4.43	17.0	31.2	1.97	15.84	12.5	0.21	0.14	0.07	0.60	1.33	1.93	4.8	68.7	1.7	42.8	31.7	1.12
	21 - 70	B	4.77	73.0	20.5	1.13	18.14	15.8	0.09	0.04	0.04	0.37	1.05	1.42	2.4	73.8	0.4	38.9	53.6	1.29
SM98	3 - 12	A	4.52	82.0	42.7	2.33	18.31	12.8	0.56	0.25	0.09	1.25	1.30	2.55	9.8	51.1	5.7	35.5	38.6	1.13
	12 - 25	AB	4.69	76.0	30.8	2.03	15.15	13.5	0.44	0.17	0.07	1.02	1.35	2.37	7.5	57.1	1.6	35.8	18.0	1.20
	25 - 46	B1	4.88	69.0	24.7	1.10	22.46	9.3	0.29	0.10	0.05	0.72	1.40	2.12	7.8	66.0	1.1	34.9	38.4	1.37
	46 - 70	B2	5.09	63.0	21.3	0.78	27.31	13.0	0.24	0.08	0.04	0.69	1.23	1.91	5.3	64.1	0.0	39.1	46.0	1.47
SM99	1 - 20	A	4.75	75.0	40.1	2.38	16.86	11.0	0.40	0.24	0.10	1.07	1.18	2.25	9.8	52.2	3.7	38.0	49.2	0.97
	20 - 48	B1	4.89	61.0	16.2	2.30	7.04	12.0	0.11	0.14	0.05	0.63	1.23	1.85	5.2	66.1	0.5	24.7	55.3	1.51
	48 - 70	B2	5.07	56.0	11.8	0.92	12.86	10.3	0.14	0.06	0.05	0.63	1.05	1.68	6.2	62.5	0.1	21.3	62.1	1.65
SF	4 - 21	A	4.98	46.2	47.5	2.99	15.89	9.2	0.95	0.41	0.36	2.27	1.25	3.52	24.7	35.5	5.8	43.8	27.2	0.94
	21 - 33	AB	5.26	15.8	30.5	1.91	15.94	9.4	0.17	0.21	0.25	1.13	1.83	2.95	12.0	61.8	1.0	49.2	30.9	0.97
	33 - 70	B	5.31	12.0	30.6	1.46	20.95	10.0	0.04	0.08	0.16	0.79	1.93	2.72	7.9	70.8	0.8	57.2	33.4	1.06

⁽¹⁾ Effective CEC = Sum of Bases + Exchangeable Al

⁽²⁾ Base Saturation = Sum of Bases/CEC * 100

⁽³⁾ Al Saturation = Exchangeable Al/CEC * 100

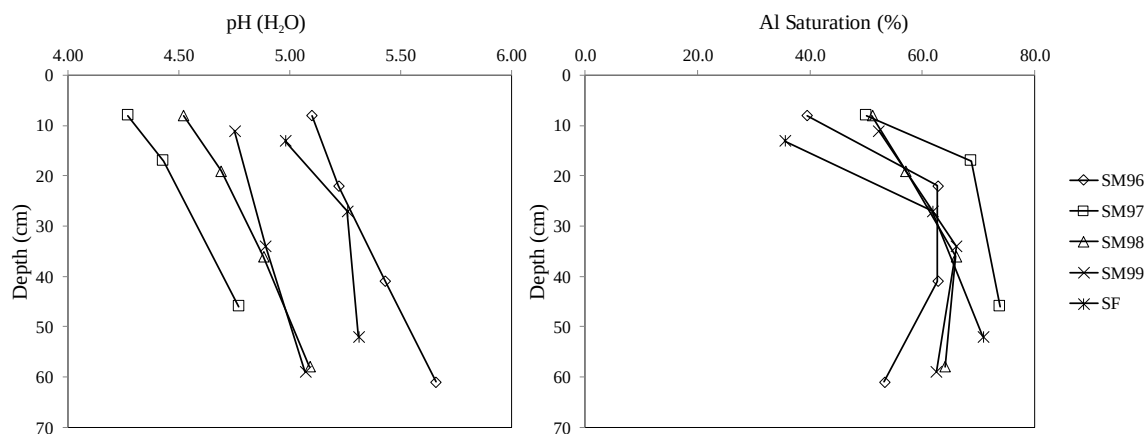


Figure 4.2: pH (H₂O) and Al saturation (%) at different depths in the study sites.

Generally, soils with high pH usually contain lesser quantities of organic matter because the soil microorganisms become more active as soil acidity decreases down the soil profiles. On the other hand, the value of Al saturation (percentage of exchangeable Al content in ECEC) of the soils in reforestation and secondary forest soil profiles was more than 35% throughout the profiles. It should be noted that the high value of Al saturation is associated with acidic soils.

The values of soil Total Carbon (T-C) and Total Nitrogen (T-N) of the studied sites are shown in Figure 4.3. The T-C content was higher at surface soil horizons as compared to subsurface soil and tends to decrease with depth in all the sites. According to Ohta and Effendi (1992), the decrease of T-C content with increasing depth also correlated with the clay content in each horizon group and the decomposition rate of soil organic matter. In this study, T-C content in A horizon from secondary forest soil profile depicted the highest value with 47.5 g/kg as compared to other sites. The thickness of A horizon was highest in the secondary forest among all studied sites. In addition, T-C content from A horizon in SM96 recorded with 46.1 g/kg, SM97 with 41.1 g/kg, SM98 with 42.7 g/kg, and SM99 with 40.1 g/kg. The soil T-C content in SM96 was slightly at the range of secondary forest due to the

recovering pool of soil carbon in order to reach the value of the typical secondary forest. Based on the *in-situ* observation during the field survey, it was suggested that the visibility of charcoal and unburned materials at subsoil layer of SM96 soil profile showed that the site was burnt previously.

Fire intensity during the previous burning which derived from the clearing of large trees was significant even at subsoil which had resulted in complete decomposition of ground biomass in SM96 site that increased the soil T-C content as well. Nonetheless, higher litterfall rate followed by lower decomposition rate usually results in high litter accumulation and high organic matter. Therefore, it can be assumed that in SM97, SM98, and SM99 sites, they produce high rates of litterfall and decomposition with the lowest value of organic matter content as compared to secondary forest and SM96. As for the soil Total Nitrogen (T-N), the results showed a decrease in soil T-N with increasing soil depth.

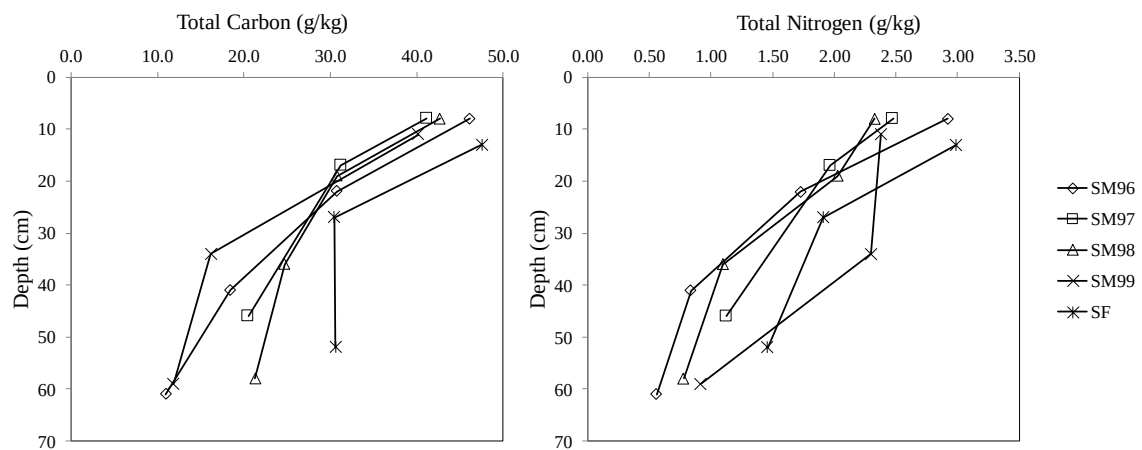


Figure 4.3: Total carbon (g/kg) and total nitrogen (g/kg) at different depths in the study sites.

Secondary forest soil profile depicted the highest value in nitrogen content in A horizon with 2.99 g/kg followed by SM96 with, 2.92 g/kg, SM97 with 2.48 g/kg, SM99 with 2.38 g/kg, and SM98 with 2.33 g/kg. However, no clear differences were observed in terms of soil T-

N. The soil T-N content was slightly higher and similar in the uppermost layer of all the study sites because of the capability of forest soils in reforestation sites and secondary forest to accumulate a large amount of organic matter, mainly supplied by the above mature vegetation (Zaidey et al., 2010).

The values of soil Effective Cation Exchange Capacity (ECEC) and soil exchangeable bases for Mg, Ca, and K is shown in Figure 4.4. In general, the soil ECEC decreases with increasing depth down the soil profile in all the study sites. Secondary forest sites recorded the highest value in ECEC as compared to the reforestation sites (SM96, SM97, SM98, and SM99). Several researchers found out that the negative charge derived from the clay minerals may have affected the CEC of the soil (Ohta et al., 1993; Sakurai et al., 1998; Tanaka et al., 2007; Arifin et al., 2008). Based on Figure 4.4, the soil exchangeable bases decreased with increasing depth. The content of exchangeable bases was higher in the surface soils than those of the subsurface soils.

According to Soto and Diaz-Fierros (1993), the higher contents of Ca and Mg in the surface soil were due to the association of biological accumulation from the plant. In addition, the exchangeable K from the decomposition of dead plants might be dissolved easily into the deep layer of soil because of heavy rainfall. High amounts of exchangeable Ca and Mg in the soils at the planting site were also assumed to result from the clear-felling and burning prior to the establishment of the rehabilitation project. Hattori et al. (2005) reported that a large amount of these cations were present in the surface layer of soils in the grassland after burning. On the other hand, Ohta and Effendi (1992) mentioned that subsoil may also play an important role as nutrient storage whereby some parts of the nutrients in the subsoil are pumped up slowly to the topsoil resulting in the accumulation of cations in the subsurface soil.

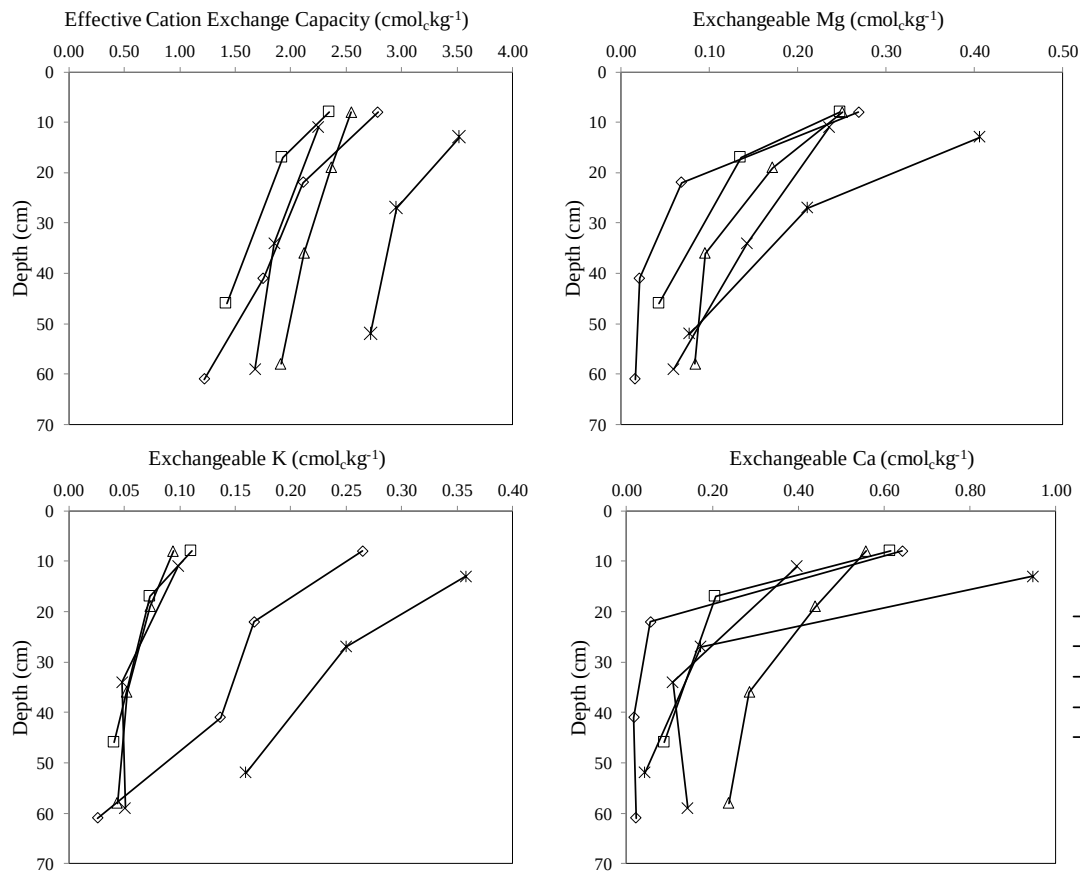


Figure 4.4: Effective cation exchange capacity (cmol_c kg⁻¹) and exchangeable bases (Mg, Ca, and K), cmol_c kg⁻¹ at different depths in the study sites.

Figure 4.5 shows the distribution of soil bulk density and soil hardness of the studied sites. The soil bulk density value increases with increasing depth throughout all the soil profiles. The reforestation plots (SM96, SM97, SM98, and SM99) had a higher bulk density as compared to the secondary forest profiles. The secondary forest had a low bulk density due to higher penetration of roots, accumulation of organic matter, and soil life. Root elongation increases the porosity of the soil. Tan (2005) reported that the pore in the soils develops due to the penetrations of roots, worms, and other forms of soil life. Bulk density is also influenced by the content of organic matter. According to Alexander (1989), higher organic matter content consequently decreased the value of the bulk density of soils. This is consistent with secondary forest soil profile since it had the highest content of organic matter.

In addition, there was a slight variation in terms of soil hardness or compactness increasing the depth down the soil profile in all study sites. The soil hardness increased with increasing depth of the soil horizons. SM96 soil profile depicted the highest value in soil hardness followed by SM98 soil profile, SM97 soil profile, SM99 soil profile, and secondary forest soil profile. Although this reflects that soil compaction did not occur and was not a limiting factor to the tree growth of *S. macrophylla*, the A horizon properties ensure the successful growth of trees in SM96. The soil hardness was significantly high probably because of the dead and carbonised tree roots of the former vegetation (Ogino et al., 2000). Meanwhile, the surface soils in the secondary forest showed a lower value of hardness than in other reforestation sites, presumably due to the presence of a relatively thick O horizon in the secondary forest (Hattori et al., 2005). Other environmental factor such as the differences in the flooding situation at the study sites could also affect the soil hardness.

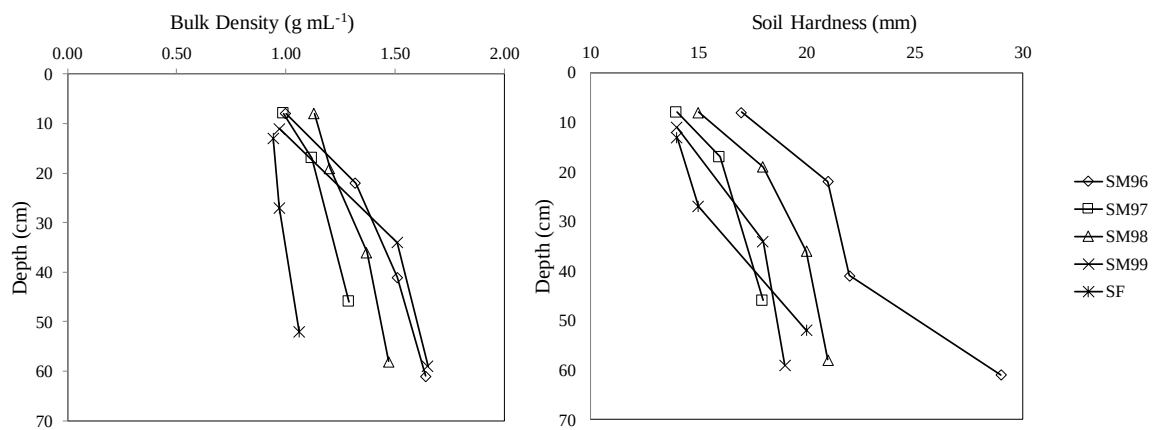


Figure 4.5: Bulk density (g mL⁻¹) and soil hardness (mm) at different depths in the study sites.

Based on the current status of soil physicochemical properties obtained, the soils at reforestation sites and secondary forest were formed from similar parent materials and consisted of different types of vegetation cover. The accumulation layer of clay mostly in B

horizon does not serve a good medium for roots to anchor the soil structure in order to maintain the body of the tree to thrive well under extreme condition such as strong winds and heavy flood. The presence of clay contributes to low water retention which may be related to the occurrence of heavy flood that happened almost every year in Sampadi Forest Reserve. In fact, this type of soil is also considered as very marginal for tree plantation establishment because of their low fertility, low nutrient, low water retention capacity, and shallow rooting depth. It can be deduced that the soils at the reforestation sites especially SM96 were slightly at the range of secondary forest due to the recovering pool of soil in order to reach the value of the typical secondary forest. In general, there were some similarities and differences among the soil properties between the reforestation sites and secondary forest.

CHAPTER 5

SURVIVORSHIP AND GROWTH PERFORMANCE OF *Shorea macrophylla* (DE VRIESE) P.S. ASHTON AFTER ENRICHMENT PLANTING FOR REFORESTATION PURPOSE AT SARAWAK, MALAYSIA

5.1 Introduction

In the humid tropics of Malaysia, indigenous tree species from Dipterocarpaceae family are mainly chosen for reforestation and forest rehabilitation purpose. Among them, *S. macrophylla* is commonly known in Sarawak, Malaysia as a medium to a large timber-sized tree and valued for its oil-bearing fruits (illipe nuts) but also considered as one of the selected species for forest rehabilitation purposes (Perumal et al., 2015). In the Mixed Dipterocarp Forests of Sarawak and Brunei, this canopy species can attain a height of 50 m tall, 4.0 m in stem girth at breast height, and 2.0 m in buttress height (Ashton, 1964; 1982).

Enrichment planting is a highly effective technique for the rehabilitation or reforestation of degraded vegetation (Appanah & Weinland, 1993; Kenzo et al., 2008). Enrichment planting trials in tropical rainforests of Malaysia date from the year 1930's (Wyatt-Smith, 1995) and have been motivated by the need to improve regenerating forests for future timber production and by the desire to restore and thereby, protect degraded unproductive areas (Appanah & Weinland, 1993; Kollert et al., 1996). For developing areas of enrichment planting, a detailed understanding of the factors controlling seedling growth and survival is required. Tang and Chew (1980) reported that although there are examples of successful line-planting programs, attempts at artificial regeneration have generally failed. Moreover, among the common problems with artificial forest regeneration were due to high maintenance costs, improper selection of planting stock, incidental damage to advance

regeneration during planting operations, and poor seedling survivorship (Pierront, 1995). Therefore, efforts to improve, evaluate, and monitor the survivorship and growth performance of planted Dipterocarp species under enrichment planting systems continue to be important (Moura-Costa, 1994).

In Sarawak, the local authority, Forest Department of Sarawak in collaboration with the participation of international NGOs from Japan have implemented reforestation programs under Friendships Forests Project by planting indigenous Dipterocarp species for the restoration of the tropical rainforest at degraded areas (Wasli et al., 2014). Such reforestation and rehabilitation efforts are especially significant in reforesting small areas deforested by shifting cultivation within the permanent forest estate and totally protected areas which would not be of an economic size for big-scale operators for plantation forest establishment. Furthermore, few researchers have stated that information on the tree growth performance and survivability of the planted indigenous tree species under reforestation effort by the local authorities in Sarawak, Malaysia is indispensable as an indicator to the successfulness of the rehabilitation efforts towards regenerating tropical forests artificially (Wasli et al., 2014; Perumal et al., 2016). Since most studies are concern with evaluation and assessment of planted trees and the changes in the surrounding ecosystem under monoculture plantation of fast-growing exotic species (Cole et al., 1996; Tilki & Fisher, 1998; Norisada et al., 2005; MacNamara et al., 2006; Arifin et al., 2008), efforts in long-term monitoring assessment on the growth performance and survivorship of planted indigenous tree species under reforestation in less diverse secondary forests are essential.

Hence, the objective of this study was to evaluate and compare the current status of survival and growth performance of *S. macrophylla* under line planting system for

reforestation and rehabilitation purposes in Sampadi Forest Reserve, Lundu, Sarawak, Malaysia.

5.2 Materials and Methods

5.2.1 Brief Information on Sampadi Forest Reserve Reforestation Sites

Sampadi Forest Reserve reforestation sites (N01°34'13''E109°53'12'') is located at Lundu, Sarawak which is approximately 72 km from southwest of Kuching City (Figure 3.1). The detail information on the topography and climatic of Sampadi Forest Reserve was mentioned in Chapter 3 of this study.

The reforestation sites were established under the secondary forests which developed from the previous history of slash and burn activities. It should be noted that all the tree seedlings were raised and cultivated for a year in the nursery and were transplanted during the community reforestation project held in the year of 1996, 1997, 1998, and 1999, respectively.

5.2.2 Methods for Assessing Tree Growth Performance and Survival of *S. macrophylla*

In terms of tree evaluation on the growth performance and survival, study plots with the size of 75 m × 50 m were constructed within the compartment planted with 150 trees of *S. macrophylla* at four different stand ages (planted in the year 1996, 1997, 1998, and 1999). It should be noted that abbreviation was coded as to represent each study plots; SM96 (*S. macrophylla* planted in the year 1996), SM97 (*S. macrophylla* planted in the year 1997), SM98 (*S. macrophylla* planted in the year 1998), and SM99 (*S. macrophylla* planted in the year 1999).

The growth assessment of the planted trees under such secondary forest cover was conducted in the year 2013 since no initial information and data was available and recorded on the condition of the seedlings at the time of planting. The assessment involved measurements such as trees total height and Diameter at Breast Height (DBH) of 1.3 m above ground level. The planted trees were measured individually in each plot using diameter tape and Suunto clinometer followed by the calculation of survival rate, respectively (Arifin et al., 2009; Perumal et al., 2014; Wasli et al., 2014). Trigonometry principles for tree height measurement were applied for taller trees where the height was taken from ground level to the point where top diameter was the minimum size for the trees (Philip, 1994). The following formula was used to calculate the survival rate of the planted *S. macrophylla* within the study plots:

$$\text{Survival rate, } X = \frac{Z}{Y} \times 100\%$$

Where:

X = Survival rate of planted *S. macrophylla*

Y = Total planted *S. macrophylla*

Z = Total number of *S. macrophylla* standing trees

As for the Mean Annual Increment (MAI) in terms of tree Total Height (MAIH) and Diameter at Breast Height (MAID), both values were estimated based on the average values of the tree height and diameter of survived trees with the stand age of the study plot. The Mean Annual Increment (MAI) were calculated by using the following formula:

$$\text{Mean Annual Increment (MAI)} = \frac{\text{Final measurement at time}}{\text{Age (years) since planting}}$$

5.2.3 Methods for Measuring Relative Light Intensity of *S. macrophylla*

The relative light intensity was measured in year 2013 under standardised conditions at 1.3 m above-ground level during a cloudy day using an Extech 401025 Digital Light Meter [Lux/ Foot-Candle (FC)] with a range of 0-2000 Foot Candle (FC) (Hattori et al., 2009b; Hattori et al., 2013). The relative light intensity measurement within the study plots were measured 25 times in each 25 m × 25 m plot. Thus, a total of 600 relative light intensity readings from the four main study plots were recorded. Open space light intensity outside the reforestation sites was measured in order to compare the light intensity under every single tree at the planted area with the open space area. Then, the measured light intensity data in Foot-Candle (FC) unit were converted into micro Einstein (μEs-1) as to obtain percentage of light intensity (%) according to the formula (Hattori et al., 2009b; Kenzo et al., 2011; Hattori et al., 2013):

$$P = [Q (FC \times 0.2)] / R \times 100$$

Where:

P = Percentage of light intensity under each tree

Q = Light intensity in Foot-Candle (FC)

R = Open space light intensity

FC × 0.2 is used to convert Foot-Candle (FC) unit to micro Einstein (μEs-1)

5.2.4 Statistical Analyses

In order to compare and determine significant differences between different stand ages of the planted *S. macrophylla*, all data of the mean annual increment in height and diameter as well as relative light intensity were statistically analysed by using a one-way Analysis of Variance (ANOVA). Tukey's HSD was chosen as post hoc tests to compare the species mean annual increments under various stand ages. All the statistical tests were performed using IBM SPSS version 21.0 for windows. Descriptive statistics (boxplots) and stacked bar charts were performed using MINITAB version 14.0 for windows.

5.3 Results and Discussion

5.3.1 Survival Rate of *S. macrophylla* in Different Stand Ages at Sampadi Forest Reserve

The assessment on the survival rate of species after rehabilitation or plantation programs especially dipterocarp trees when planted under various stand ages in a degraded forest is vital and required towards better recommendation of species selection in the future. The survival and mortality rates for planted *S. macrophylla* under various stand ages in all the study plots of SM96, SM97, SM98, and SM99 are shown in Table 5.1.

The result shows that the survival rate of planted *S. macrophylla* in SM96, SM97, SM98, and SM99 plots were 88, 80, 82, and 57%, respectively. The highest survival was with 88% from the SM96 plot and the lowest survival was from the SM99 plot with the percentage of survival, 57%. A total of 23% (139 trees out of 600 trees) of *S. macrophylla* did not survive among all the study plots from SM96, SM97, SM98, and SM99. In terms of the percentage of mortality, plot SM99 depicted the highest percentage value as compared to other studied plots.

Table 5.1: Survival and mortality rates of planted *S. macrophylla* at different stand ages.

Study sites	Year planted	Age (years)	Number of trees planted	Number of trees survived	Survival rate (%)	Mortality rate (%)
SM96	1996	18	150	132	88	12
SM97	1997	17	150	120	80	20
SM98	1998	16	150	123	82	18
SM99	1999	15	150	86	57	43

High light irradiance could be one of the possible factors which may reduce the survivability of the planted species in plot SM99. Light intensity factor had a particularly large influence on the SM99 plot due to the wide gap of canopy openness which enabled the sunlight to penetrate downward through the canopy of the *S. macrophylla* trees. Based on the previous study by Hattori et al. (2013), it was reported that high light intensity reduced the seedling survivability of both over 0-24 months and 24-81 months planted dipterocarp forest species. On the contrary, Ådjers et al. (1995) reported that planted *Shorea parvifolia* and *Shorea leprosula* for a period of 26 months exhibited better height and basal diameter in the 2 and 3 m line planting widths compared to 1 m, reflecting sufficient amount of overhead light. Thus, the opening of the vegetation canopy plays a vital role with the species-specific light requirement to promote higher survival and growth rates of the planted *S. macrophylla*.

The percentage of survival and mortality are crucial in order to understand the mechanisms that affect the dynamics of the tree population and vital to effectively manage that population and its habitat. Previous reports on enrichment planting of various dipterocarp species in Southeast Asia also showed higher interspecific differences in seedling mortality ranging from only a few percent to almost 100% (Appanah & Weinland,

1993; Ang & Maruyama, 1995; Ådjers et al., 1996). Vincent and Davies (2003) stated that in general, planting dipterocarps in logged and degraded forests have reported substantially higher mortality in most studies. Suhaili et al. (1998) reported that the percentage of seedling mortality was 22% for *Shorea parvifolia* over the first 6 months after planting on a degraded logged over forest in Negeri Sembilan, Peninsular Malaysia. Ådjers et al. (1996) showed seedling mortality of 30.0 to 62.5% in a degraded secondary forest in South Kalimantan, Indonesia. In contrast, Vincent and Davies (2003) reported significantly lower seedling mortality of less than 6% over 22 months in a degraded secondary forest of Sarawak. In their study, high monthly rainfall throughout the first year of the experiment may have enhanced seedling survival (Vincent & Davies, 2003). Nevertheless, the percentage of mortality have been 20 to 50% in the first few years and sometimes even higher in several other dipterocarp plantation studies in South East Asia (Ådjers et al., 1995; Ang & Maruyama, 1995; Ådjers et al., 1996).

Environmental factors may also have a great influence on the survival and growth performance of the tree species such as light intensity, soil fertility, mineral nutrients, and water holding capacity. According to Evans (1992), environmental factors such as drought season, diseases, planting technique, and weed competition influence the growth performance and survival of planted species. In addition, among the two major factors that usually influence the seedlings survival are light intensity and the amount of available moisture especially during the initial stage of stand establishment.

5.3.2 Growth Performance of *S. macrophylla* under Different Stand Ages at Reforestation Sites

The number of enumerated trees and total height distribution of planted *S. macrophylla* at various stand ages in Sampadi Forest Reserve is shown in Figure 5.1. Based on the stacked bar chart obtained, the frequency of enumerated trees with the height class of 5.01 to 10.00 m shows the highest with a total frequency of 211 trees among all the four study plots surveyed; SM96, SM97, SM98, and SM99. This followed by the height class of 10.01 to 15.00 m with a total of 143 trees, ≤ 5.00 m class with 64 trees, and 15.01 to 20.00 m class with 34 trees. Less than 10 trees with the size exceeding the height of more than 20.00 m were observed.

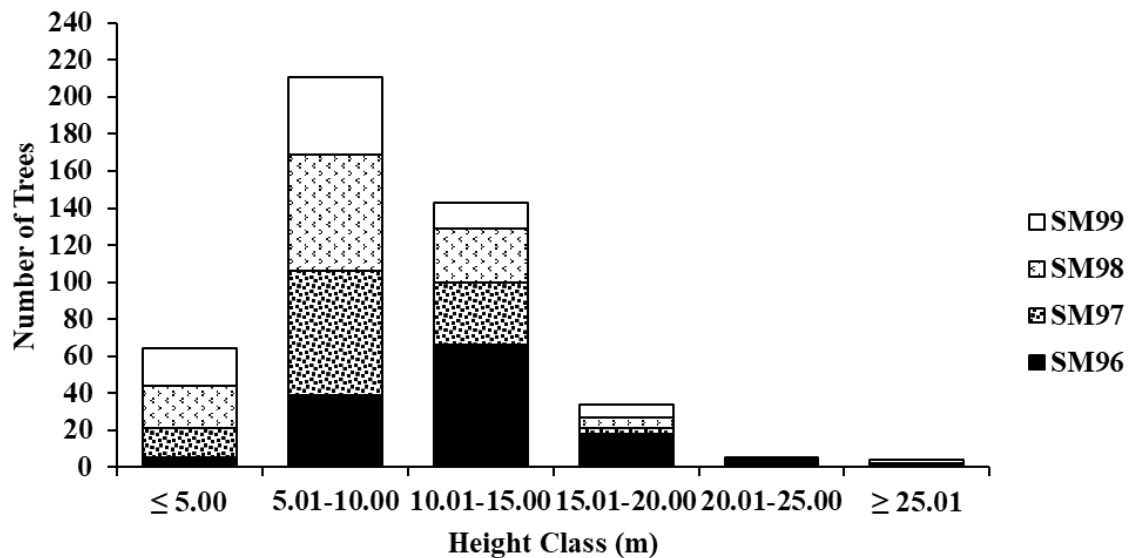


Figure 5.1: Total tree height (m) distribution of planted *S. macrophylla* in SM96, SM97, SM98, and SM99.

Figure 5.2 shows the mean total height of *S. macrophylla* in all study sites. The results show that the mean total height of *S. macrophylla* in SM96, SM97, SM98, and SM99

were 11.77, 8.59, 8.27, and 8.75 m, respectively. The mean total height of planted *S. macrophylla* in the SM96 was higher as compared to SM97, SM98, and SM99 plots. SM98 recorded the lowest mean value among all study plots.

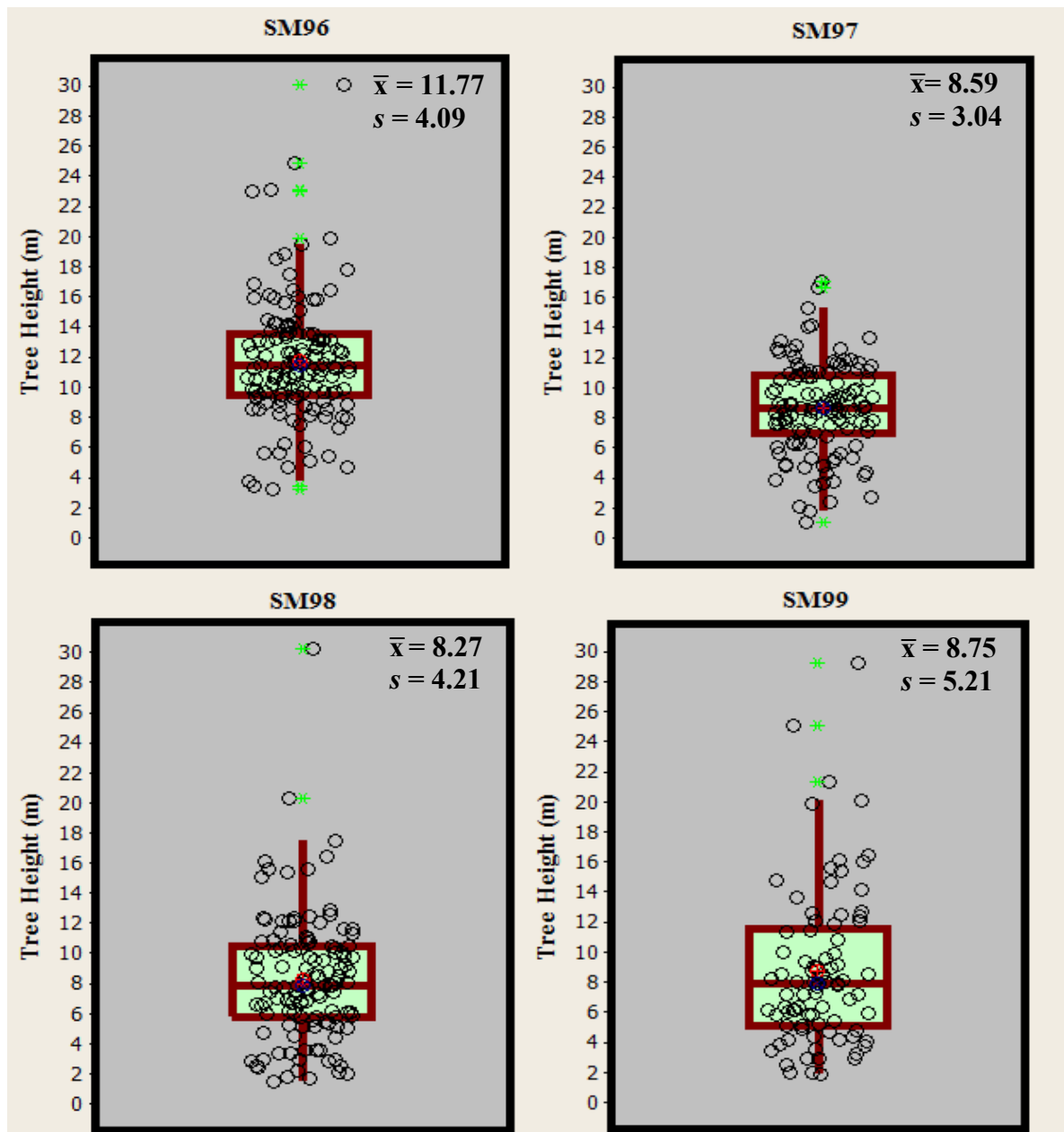


Figure 5.2: Mean total height (m) of planted *S. macrophylla* at different stand ages. $\bar{x}$ and s refer to mean and standard deviation, respectively.

The number of enumerated trees and Diameter at Breast Height (DBH) distribution of planted *S. macrophylla* at various stand ages in Sampadi Forest Reserve is shown in Figure 5.3. Based on the stacked bar chart obtained, the frequency of enumerated trees with the diameter class of 5.1 to 10.0 cm showed the highest with a total frequency of 197 trees among all the four study plots surveyed; SM96, SM97, SM98, and SM99. This followed by the diameter class of 10.1 to 15.0 cm with a total of 115 trees, ≤ 5.0 cm class with 77 trees and 15.1 to 20.0 cm class with 57 trees. There was only a total of 12 trees in diameter class 20.1 to 25.0 cm. Less than 5 trees with the size exceeding the diameter at breast height of more than 25.1 cm were observed.

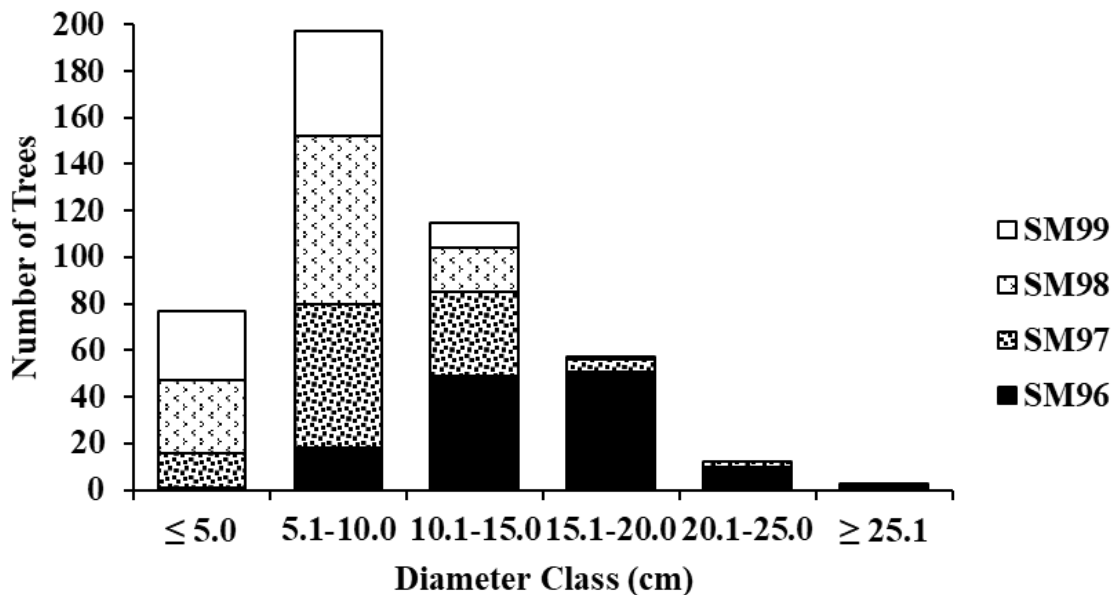


Figure 5.3: Diameter at breast height (cm) distribution of planted *S. macrophylla* in SM96, SM97, SM98, and SM99.

Figure 5.4 shows the mean diameter at breast height of *S. macrophylla* in all study sites. The results show that the mean diameter at breast height of *S. macrophylla* in SM96, SM97, SM98, and SM99 were 14.7, 9.3, 7.0, and 6.6 cm, respectively. It was observed that

the mean size of the trees decreases and was directly proportional to the increasing planting age of *S. macrophylla*. The mean diameter at breast height in SM96 was higher as compared to SM97, SM98, and SM99 plots. SM99 depicted the lowest average in mean value among all study plots.

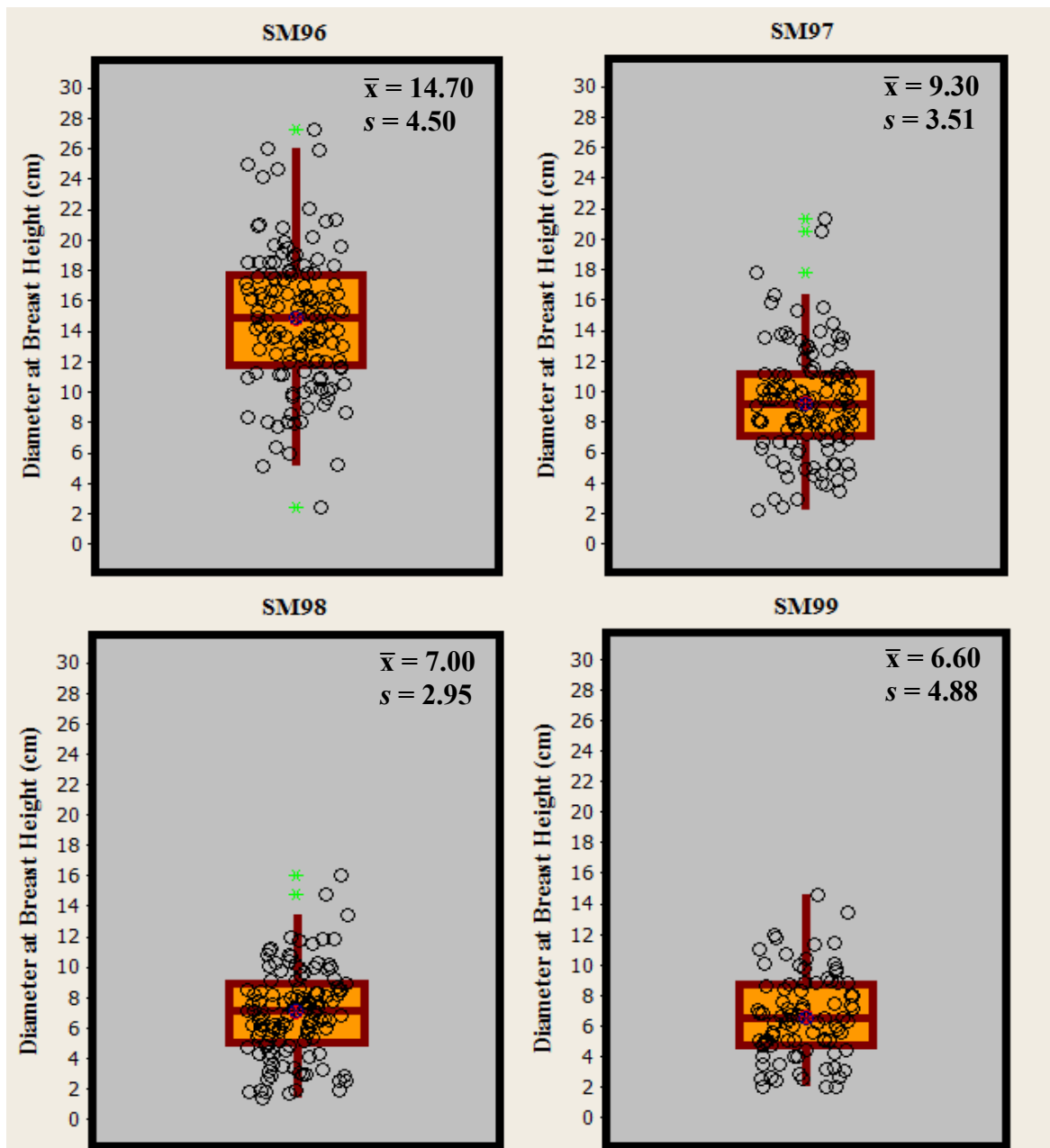


Figure 5.4: Mean diameter at breast height (cm) of planted *S. macrophylla* at different stand ages. $\bar{x}$ and s refer to mean and standard deviation, respectively.

There was a strong relationship between two growth parameters (diameter at breast height (DBH) and total height) of the planted *S. macrophylla* trees. The relationship between diameter at breast height and total height of all the planted trees for assessment was illustrated in Figure 5.5. The illustration shows that the diameter at breast height was directly proportional to the total height whereby an increase in diameter at breast height was followed by an increase in the total height. A high positive correlation was found between the diameter at breast height with total height ($R^2 = 0.8194$, $P < 0.01$) with a linear equation of “ $y = 0.53x + 4.16$ ”, where ‘y’ is the total height (m) and ‘x’ is the diameter at breast height (cm).

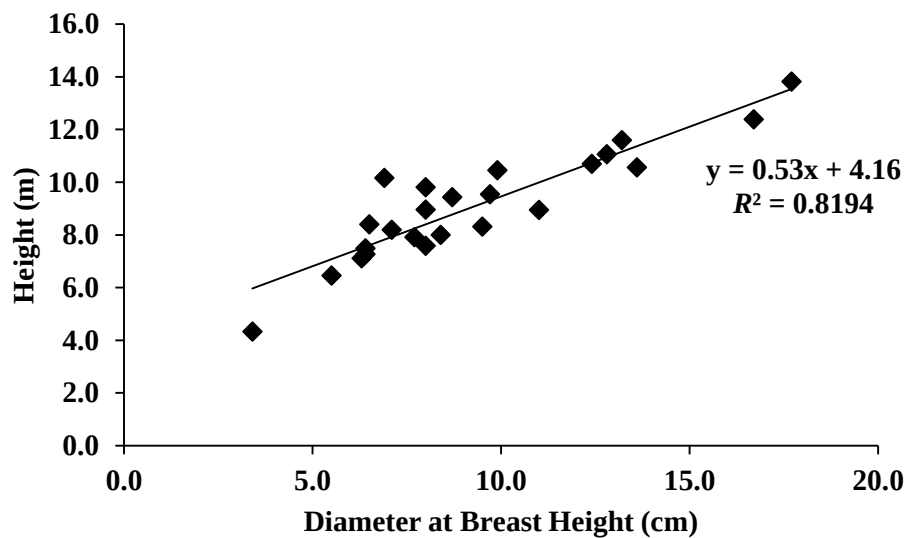


Figure 5.5: Relationship between diameter at breast height (DBH) and total height of the planted *S. macrophylla* in SM96, SM97, SM98, and SM99 study sites.

On the other hand, strong relationships were also found between the tree height and diameter at breast height with the age of the planted *S. macrophylla*. Based on Figure 5.6 and Figure 5.7, a moderate positive correlation was obtained for tree height with $R^2 = 0.4823$, whereas a strong high positive correlation was recorded for diameter at breast height with $R^2 = 0.6949$. This indicated that both height and diameter at breast height of the planted *S.*

macrophylla increased with planting age, except for plot SM99 whereby the height was greater than SM97 and SM98 study sites.

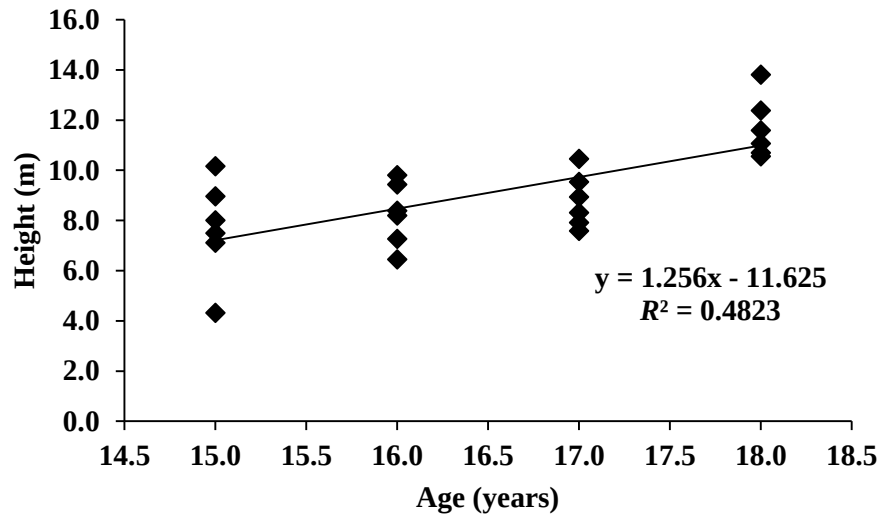


Figure 5.6: Relationship between total height and age of the planted *S. macrophylla* in SM96, SM97, SM98, and SM99 study sites.

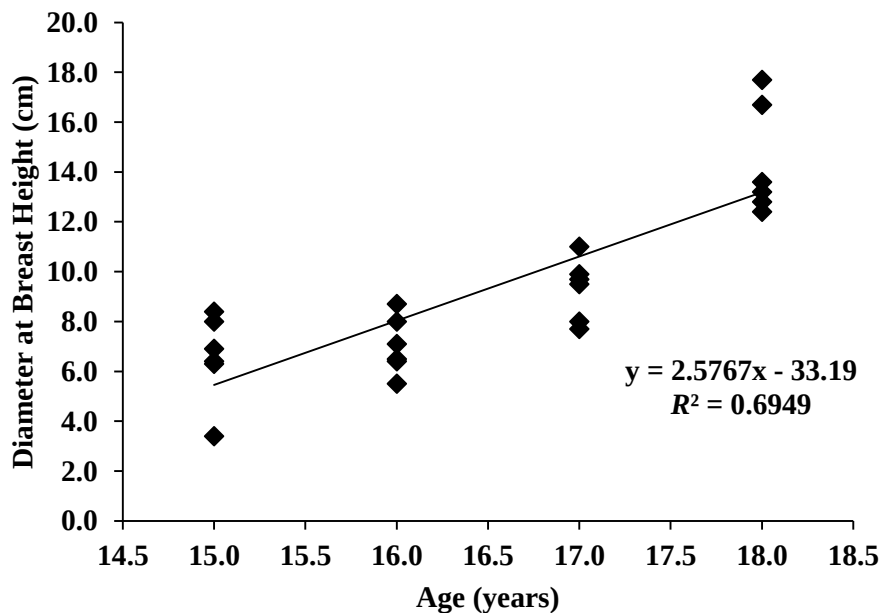


Figure 5.7: Relationship between diameter at breast height and age of the planted *S. macrophylla* in SM96, SM97, SM98, and SM99 study sites.

5.3.3 Relative Light Intensity in SM96, SM97, SM98, and SM99 *S. macrophylla* Plots

The results in Figure 5.8 show that the mean relative light intensity of planted *S. macrophylla* in plot aged 18 years (SM96) was significantly higher than the rest of the mean relative light intensity in plot aged 17 years (SM97), plot aged 16 years (SM98), and plot aged 15 years (SM99). The mean relative light intensity in plot SM96 depicted the highest among other plots with 6% light intensity. On the other hand, the mean relative light intensity for plot SM99 was 4%. The lowest mean relative light intensity recorded were 2% and 1% in both plots; SM97 and SM98, respectively, although the differences were statistically significant.

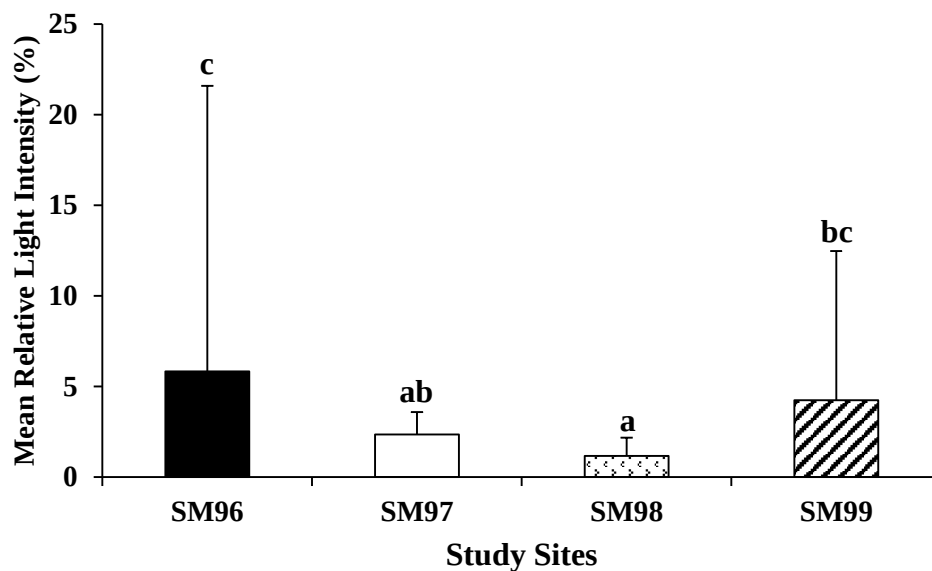


Figure 5.8: Mean relative light intensity (%) of planted *S. macrophylla* in SM96, SM97, SM98, and SM99 study sites. Different letters indicate significance differences at $P < 0.05$ using Tukey HSD test.

According to Hattori (2005), the growth performance of planted dipterocarp seedlings is affected by various environmental factors such as light intensity and soil fertility. Light is an important ecological factor which plays a major role in the recruitment of saplings of the forest and both the quality and quantity changes as light passes through canopy

(Bazzaz, 1996). Weidelt (1996) reported that the most important conditions for success of line planting are light control. Most shade-tolerant tree seedlings require light from canopy gaps for survival and growth into canopy-sized trees (Swaine & Whitmore, 1988; Platt & Strong, 1989). Even within a single area to be planted, the factors may vary widely due to the spatial and temporal variability in disturbances as well as variability in microtopography. Thus, light condition was one of the influential factors for growth of *S. macrophylla* based on the results obtained in this study.

In plot SM96, the effect of canopy openness on the growth of *S. macrophylla* may be related to their sensitive reaction to light condition as well as wide variation of the canopy openness in their plots. This enhances the amount of sunlight that penetrates downward through the canopy to the *S. macrophylla* trees. A higher mortality rate with 43% for planted *S. macrophylla* trees was reported in study plot SM99 as compared to plot SM96 with 12% of mortality rate. This showed that the higher light intensity caused less mortality of planted trees in SM96, and also enhanced the growth of the planted trees that survived but however in plot SM99, although the mean light intensity was slightly higher than SM97 and SM98, the mortality rate was still being highest among all the study plots. This is because in plot SM99 the canopy openness was rather wide which enables the sunlight to penetrate downward through the canopy to the *S. macrophylla* trees.

On the other hand, highest mortality rate in plot SM99 among all the study plots was recorded due to the poor soil properties in the specific study site. In addition, competition between *S. macrophylla* and pioneer tree species for sunlight also significantly affected the mortality rates in which, had a large impact on the growth performance of *S. macrophylla*. Therefore, in order to reduce this competition, frequent silvicultural practices like thinning operation and removing of the recruits of local pioneer tree species should be carried out for

the enhancement of tree growth in the study plot. In Sabah, selective felling, selective girdling and sub-canopy slashing by cutting small tree with diameter at breast height (DBH) less than 10 cm were carried out in enrichment planting site under secondary forest dominated by *Macaranga* spp. (Ådjers et al., 1995).

In contrast to plot SM97 and SM98, the mean light intensity was low due to the rapid growth of pioneer trees in the study plot. Pioneer tree species such as *Macaranga* spp., *Dillenia suffructicosa*, as well as few existences of light demanding herbaceous species dominated the undergrowth vegetation as well as the vegetation in between the planting lines. Although the level of light intensity was low in both plots, it had no clear effects on the mortality of planted trees whereby the survival rate of planted trees in both plots were 80% and 82%, respectively. As a whole, the light intensity condition of the study sites had provided less impact on the growth performance of the planted *S. macrophylla* trees especially in SM97 and SM98 plots. Numerous studies reported the relationship between dipterocarp trees and relative light intensity and is reasonably well-known (Ang, 1991; Ådjers et al., 1996; Itoh et al., 1999; Schwarzwaller et al., 1999). In addition, several studies also mentioned that the growth rate and survival of dipterocarp under enrichment planting are consistently better in moderate light levels (below 30% of relative light intensity) than in high light levels (more than 50% of relative light intensity) (Ang, 1991; Ådjers et al., 1995; Raja Barizan, 1996; Raja Barizan & Appanah, 1997; Ashton et al., 2006).

According to Perumal et al. (2012), a high density of pioneer species in plot SM99 could be another reason why most of the growth of *S. macrophylla* in SM99 was poor. On the other hand, the growth performance in terms of mean annual increment in height and diameter in SM96 was better as compared to plot SM98 and SM99. Good height and diameter growth of the species could be due to the good adaptability of planted *S.*

macrophylla to the locality or species-site matching and ability to tolerate water stress and other unfavourable site conditions (Perumal et al., 2012). Azani et al. (2003) described that the variation in growth of planted species is due to the specific reaction of the species to environmental conditions such as climate, soil, and topography. Furthermore, growth in terms of height and diameter increment is also influenced by the availability of space between trees (Mohd Zaki et al., 2003).

The results for mean annual increments in height (MAIH) and diameter at breast height (MAID) among species after 18, 17, 16, and 15 years of planting are shown in Table 5.2. There were significant differences ($P < 0.05$) of the mean annual increments in height and diameter among *S. macrophylla* being planted in the study plots, especially in plot SM96. The average value of the mean annual increment of height (MAIH) of *S. macrophylla* planted in SM96 (0.65 m year^{-1}) recorded the highest MAIH of planted trees among the plots surveyed, followed by SM99 with MAIH 0.58 m year^{-1} , SM98 (0.52 m year^{-1}) and the lowest SM97 (0.51 m year^{-1}). In addition, the average value of the mean annual increment of diameter (MAID) of planted trees in SM96 ($0.82 \text{ cm year}^{-1}$) attained significantly higher MAID than SM97 ($0.55 \text{ cm year}^{-1}$), SM 98 ($0.44 \text{ cm year}^{-1}$) and SM99 ($0.44 \text{ cm year}^{-1}$), respectively.

Generally, in terms of mean annual increments of height and diameter, the growth performance of planted *S. macrophylla* was relatively poor. Even though these mean annual increments (MAI) were relatively slow after 18 years of planting, *S. macrophylla* still can adapt well and survive under harsh conditions such as annual flooding (Figure 5.9).

There were no similar characteristics observed and found in terms of growth as compared to the early establishment of the plantation was done. Nevertheless, *in-situ* observation suggested that factors such as competition between the existing pioneer species

as well as topographical features in all the study sites may have contributed to differences in terms of MAIH and MAID in SM96, SM97, SM98, and SM99. Similar findings on the factors influencing the growth performance and survival of *Dryobalanops beccarii* were reported and highlighted by Wasli et al. (2014) in Gunung Apeng Forest Reserve, Sarawak. In addition, Itoh et al. (2003) stressed that soil properties such as soil texture and topographical features had largely affected the spatial distribution of dipterocarp species under natural tropical rainforests.

Table 5.2: Mean annual increment in height (MAIH) and mean annual increment in diameter (MAID) of planted *S. macrophylla* at different stand ages in this study and other previous studies on reforestation in Malaysia.

Studied species	Stand age (years)	MAIH (m year ⁻¹)	MAID (cm year ⁻¹)	Planting technique	Source
<i>Shorea macrophylla</i>	18	0.65 b	0.82 c	Line planting	Present study
<i>Shorea macrophylla</i>	17	0.51 a	0.55 b	Line planting	Present study
<i>Shorea macrophylla</i>	16	0.52 a	0.44 a	Line planting	Present study
<i>Shorea macrophylla</i>	15	0.58 ab	0.44 a	Line planting	Present study
<i>Shorea leprosula</i>	6	1.08	1.10	Open planting	Hamzah et al., 2009
<i>Shorea parvifolia</i>	6	1.00	1.01	Open planting	Hamzah et al., 2009
<i>Shorea leprosula</i>	12	1.24	1.44	Multi-storied forest planting	Arifin et al., 2008
<i>Shorea parvifolia</i>	12	1.01	1.20	Multi-storied forest planting	Arifin et al., 2008
<i>Shorea pauciflora</i>	11	0.67	0.74	Line planting	Arifin et al., 2008
<i>Shorea macroptera</i>	11	0.61	0.67	Line planting	Arifin et al., 2008
<i>Shorea pauciflora</i>	11	0.77	1.08	Gap planting	Arifin et al., 2008
<i>Shorea macroptera</i>	11	0.74	0.86	Gap planting	Arifin et al., 2008

Different letters within the same column of studied species, *S. macrophylla* indicate significant differences at $P < 0.05$ using Tukey HSD test.

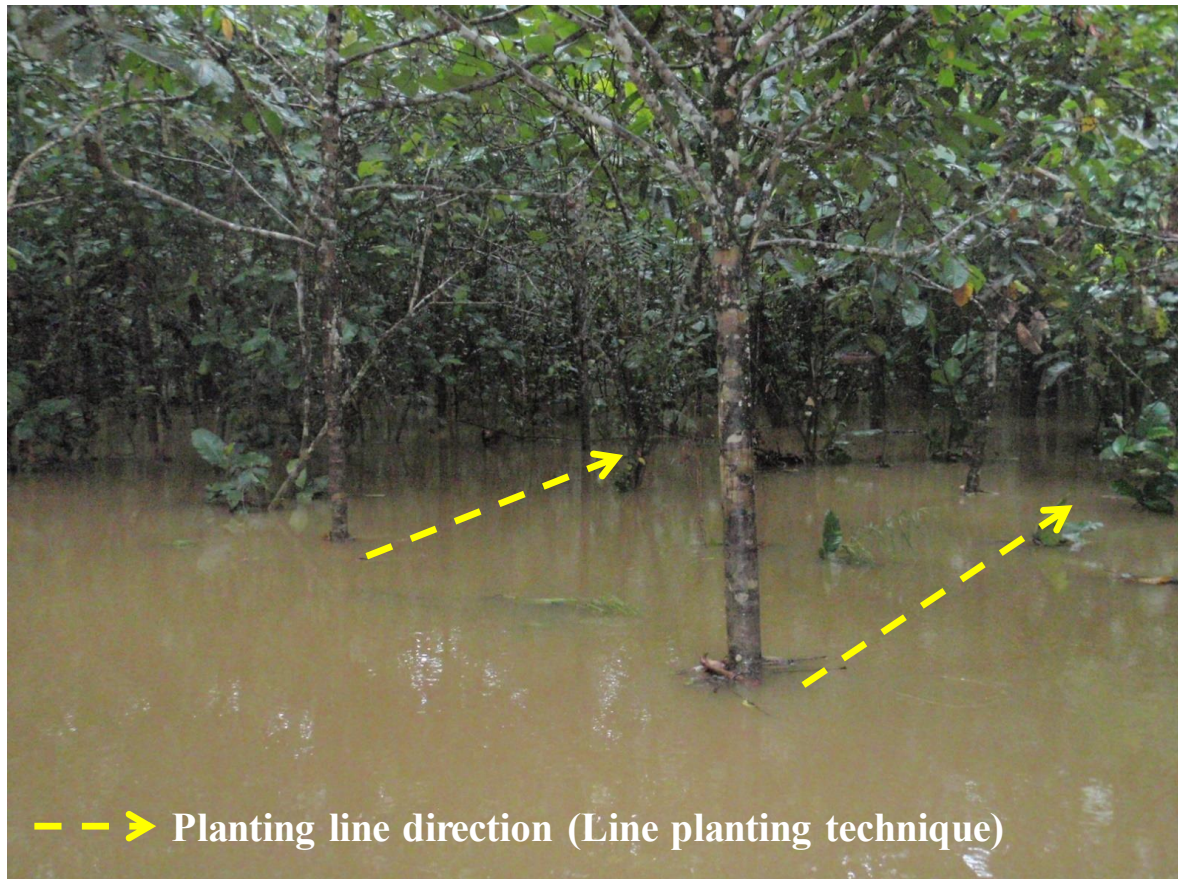


Figure 5.9: Periodic inundation at Sampadi Forest Reserve reforestation sites.

5.3.4 Suitability, Adaptability, and Growth Performance of *S. macrophylla* at Sampadi Forest Reserve and other Previous Studies on Forest Rehabilitation in Malaysia

In order to clarify the fundamental information on the suitability of *S. macrophylla* as one of the suitable species selected for future reforestation and rehabilitation purposes in Sarawak, findings on experimental reforestation by using indigenous dipterocarp tree species under various forms of enrichment planting techniques from previous studies in Malaysia and present study was shown in Table 5.2. Even though the performance of planted tree species and edaphic factors in previous studies varied from this study, it should be noted that the tree species used in these studies are of the same family (Dipterocarpaceae) and the discussion

from this study is principally to obtain information on whether *S. macrophylla* is well-suited tree species for future reforestation and rehabilitation purposes.

In the present study, regardless of the differences in stand age after planting, planting techniques, and types of planted tree species, the mean annual increment in height (MAIH) and diameter (MAID) of *S. macrophylla* planted in SM96, SM97, SM98, and SM99 were lower as compared to the results reported by Hamzah et al. (2009) and Arifin et al. (2008). Nonetheless, the mean annual increment in height (MAIH) and diameter (MAID) of *S. macrophylla* were lower as compared to planted *S. pauciflora* and *S. macroptera* under both line and gap planting techniques.

According to Arifin et al. (2008) and Hamzah et al. (2009), the effect of extreme heat, strong winds, and overexposure of light to the planted seedlings under open planting could be the major reason behind the low survival of planted *S. leprosula* and *S. parvifolia* in their study. In addition, Suhaili et al. (1998) reported that the full sunlight received by the seedlings has caused scorching of leaves hence resulting in a low percentage of survival. Based on the current study, although the survival of the planted *S. macrophylla* in Sampadi Forest Reserve was substantially higher due to the well-adaptability of this species under specific soil conditions or site characteristics in the study sites, it is expected that in the future, the percentage of survival of *S. macrophylla* will decline when the planted trees reached its maximum maturity due to competition for space, available nutrients in soil, and light requirement for the planted trees. In the case of planted dipterocarp species like *Shorea* spp., several researchers have also reported a similar trend of low survival when involving planting dipterocarp species on the degraded secondary forest. For example, Azman et al. (1990) reported that *S. leprosula* and *S. parvifolia* survival of 30 and 20%, respectively at 15 years after planting. In addition, Ådjers et al. (1996) reported that the survival of planted ten

dipterocarp species varied widely from 5.9 to 77.8% after three years of planting in degraded secondary forest subjected to shifting cultivation in Kalimantan, Indonesia. Dipterocarp species shows relatively slow growth rate but it is adapting well to sufficient amount of sunlight when planted on land with poor soil properties (Appanah & Weinland, 1993; Ådjers et al., 1996; Vincent & Davies, 2003).

Environmental factors such as weather condition in terms of sunlight intensity, pest attack (termites), animal distribution, planting technique, weed competition, and poor soil condition are the factors possibly could lead to variation in growth performances and survival of dipterocarp species (Evans, 1992). A study by Hattori et al. (2006) reported that *S. macrophylla* is susceptible to termite attack. The sap-sucking insect, *Helopeltis clarifer* has been recorded to kill seedlings in the nursery. Moreover, growing space also may contribute to growth performance (Mohd Zaki et al., 2003).

One of the advantages adopting enrichment planting such as line planting technique is that it enables the local vegetation such as some kind of undisturbed pioneer species which has grown naturally before the establishment of reforestation site to provide optimal shade condition for the planted dipterocarp seedlings. Nevertheless, silvicultural activities can be conducted easily as the spaces between the planted seedlings are uniform. Notwithstanding, good silvicultural activities under this form of planting technique in the reforestation area at Sampadi Forest Reserve should be considered as tree species like *Dillenia suffructicosa* and *Macaranga* spp. in SM96, SM97, SM98, and SM99 would generate competition for light and space with the planted *S. macrophylla*. As described by Arifin et al. (2008), the percentage survival of planted *Shorea* spp. was significantly higher under narrow than the wider opening of both line and gap planting techniques in Peninsular Malaysia. Generally,

dipterocarp seedlings have been found to survive better in shaded sites as compared to open sites (Ådjers et al., 1996; Romell et al., 2007).

In conclusion, the assessment on the survivorship and growth performance of *S. macrophylla* after enrichment planting under various stand ages indicated a considerable tree growth which clarified the efficacy of line planting system used in Sampadi Forest Reserve. The findings implied that *S. macrophylla* is suitable for forest rehabilitation purpose in the study area and the positive outcome could be achieved from this reforestation effort on the long run. Nonetheless, high survival percentage associated with substantial growth rate in terms of diameter and height of *S. macrophylla* could be due to the good adaptability and survivability of this species which can grow under certain soil condition or competition for light between planted trees and naturally grown vegetation which was undisturbed with the planting line.

CHAPTER 6
ASSOCIATION BETWEEN SOIL FERTILITY AND GROWTH PERFORMANCE
OF PLANTED *Shorea macrophylla* (DE VRIESE) P.S. ASHTON AFTER
ENRICHMENT PLANTING AT REHABILITATION SITES OF SAMPADI
FOREST RESERVE, SARAWAK, MALAYSIA

6.1 Introduction

Many countries throughout the world are facing acute scarcity of lands for food production due to the rapid increase of population and limited land resources, which causes people to convert forest land into agricultural, horticultural, plantations, and pastoral land for cattle settlements or mining (Panwar et al., 2011). Such human activities have led to the depletion of existing forests throughout the world, particularly in Asian countries. In the tropics, approximately 60% or 850 million hectares of the total forest area between the year 1950 and 2000 have been degraded and are difficult to regenerate due to chemical, biological, and physical barriers (ITTO, 2002). Consequently, this has led to the attention of developing restoration or rehabilitation practices on degraded secondary forest (Ramos & del Amo, 1992; Ådjers et al. 1995; Otsamo, 1998; Vincent & Davies, 2003; Ilstedt et al., 2004) as to preclude further degradation (Lugo, 1997; Parrotta et al., 1997) by means of improving the site productivity and quality (McDill & Amateis, 1992; Onyekwelu, 2005). According to Doi and Sakurai (2004), measuring soil quality using soil indices is essential to estimate the soil productivity or to rehabilitate degraded lands. Enrichment planting system has been used as one of the promising techniques to recover and restore the degraded forestland in the tropics (Ramos & del Amo, 1992; Ådjers et al. 1996; Montagnini et al., 1997).

Restoration of degraded forestland is indispensable to reduce soil nutrient loss and improve vegetation composition or stand for the purpose of environmental conservation (Zaidey et al., 2010). Rehabilitation efforts in degraded forestland due to abandoned shifting cultivation have been successfully implemented under the ecosystem rehabilitation (Kendawang et al., 2004) and by enrichment planting technique (Wasli et al., 2014; Perumal et al., 2017a) in Sarawak, Malaysia. In Sarawak, one of the common indigenous tree species from Dipterocarpaceae family, *S. macrophylla*, was considered and selected for forest rehabilitation purposes (Perumal et al., 2015, 2017a). This canopy species was chosen since it is one of the fastest growing species of the genus *Shorea* and is found frequently along rivers and in areas which are periodically inundated. Likewise, in Peninsular Malaysia, rehabilitation of forestland that is degraded due to excessive harvesting has been reforested through the technique of enrichment planting (Appanah & Weinland, 1993; Arifin et al., 2008; Affendy et al., 2009; Hamzah et al., 2009).

Knowledge of soil science for the better understanding of the effective soil management and conservation is required for the rehabilitation of tropical rainforest on the land that is severely degraded. Consequently, a multivariate strategy can be implemented to measure the soil quality. Since properties of the same soil may respond differently to a degrading impact (Jha et al., 1992), it is expected to be more informative to quantify and integrate various soil variables than measuring a single variable (Doi & Sakurai, 2004). A multivariate soil data set is regarded as integrated properties of the soil. According to Sena et al. (2000), integrating multiple soil physicochemical properties with the use of a multivariate statistical technique often provides new measures that explain variations among the soils.

Principal Component Analysis (PCA) is one of the proposed multivariate statistical techniques used to measure and explain the differences among soils. In PCA, a multivariate data set is analysed to reduce the original complicated dimensionality and to give a few principal components (PCs) that explain the variation in the data (Doi & Sakurai, 2004; Arifin et al., 2008). Thus, data redundancy is avoided and the most significant PCs which explain the difference are specified. Previous studies have emphasized using PCA to identify PCs and important soil physicochemical properties relating to the incidence of plant disease (Domínguez et al., 1996), soil formation reflecting landscape (Seelig et al., 1991), and other types of gradient.

However, for the case of Sarawak, Malaysia, intensive research has to be done on the elucidation of soil properties based on PCA and soil indices after enrichment planting in relation to the productivity of the potential dipterocarp species in rehabilitating degraded forestland. Moreover, attention has to be paid to the status of soil physicochemical properties after rehabilitation since most of the previous researches have underlined the growth performance of planted species along with the different technique of planting (Perumal et al., 2014, 2015). In addition, information on the soil-plant relationship of indigenous species and soil fertility status which might influence the survivorship and growth performance of planted species under rehabilitation even after 14 years of the research is necessary for future forest management programs. On the other hand, Hamzah et al. (2009) stated that more comprehensive research has to be conducted on site productivity which could be improved by clarifying the potential of dipterocarp species in rehabilitating degraded forestland.

Therefore, in order to improve strategies and effective technique for future rehabilitation efforts, an evaluation study of the rehabilitation program in relation to growth performance of planted species and soil fertility status by using PCA and soil indices could

deliver significant information on species site preference (Arifin et al., 2008). The main emphasis was placed on finding the significant soil properties based on PCA and the applicability of the proposed indices, the Soil Fertility Index (SFI) (Moran et al., 2000b) and the Soil Evaluation Factor (SEF) (Lu et al., 2002) as an alternative approach of indicator for estimating soil fertility and site quality in the plantation for rehabilitation purposes in relation to the survivorship and growth performance of the planted species. Lu et al. (2002) mentioned that, for a homogeneous forest with similar vegetation ages, soil indices are often used to evaluate the soil conditions, and the dominant tree height is usually used to model the site indices.

Hence, the aim of this study was to determine the status of soil physicochemical properties under enrichment planting in comparison to an adjacent secondary forest at Sampadi Forest Reserve, Lundu, Sarawak, Malaysia. In addition, the present study also intended to evaluate the effect of enrichment planting of *S. macrophylla* on the soil fertility status with special reference to Soil Fertility Index (SFI) and Soil Evaluation Factor (SEF). These indices suggested the applicability to the estimation of soil fertility and to the prediction of the increase in biomass, in Amazonian humid tropical forests under secondary succession. The score on the PC, as a measure of changes of soil physicochemical properties after enrichment planting, correlates with the SFI and/ or the SEF was investigated.

6.2 Materials and Methods

6.2.1 Background and Information on Sampadi Forest Reserve Rehabilitation Sites and Secondary Forest

The present study was conducted in a forest under enrichment planting at Sampadi Forest Reserve, Lundu, Sarawak (N01°34'13''E109°53'12'') and an adjacent secondary forest

(N01°30'26.2''E109°58'56.7'') which is located about 72 km from southwest of Kuching City (Figure 2.1). The detail information on the topography and climatic of Sampadi Forest Reserve was mentioned in Chapter 3 of this study. According to our previous study at the area, the morphological characteristics of the soil resemble Bako soil series as a dominant unit in association with Saratok series and are categorised mainly under the soil group of Grey-White Podzolic Soil based on the Sarawak soil classification system (Andriessse, 1972; Perumal et al., 2015). The soils in the study area were derived from a mixture of sandstone, coarse-grained, humult ultisols, and sandy residual parent material (Perumal et al., 2014, 2015). Based on the USDA-NRCS classification system, this soil group corresponds to Typic Paleaquults of Soil Taxonomy (Teng, 2004; Soil Survey Staff, 2014; Perumal et al., 2015). Based on the general *in-situ* observation, the current stand characteristics of the secondary forests and forest within the enrichment planting were almost similar. The detail information on the general land use history and vegetation of Sampadi Forest Reserve was mentioned in Chapter 3 of this study.

6.2.2 Experimental Design and Methods for Soil Sampling

In order to elucidate the soil properties in greater detail, six experimental plots sized 25 m × 25 m in the rehabilitation sites were constructed for the four stand ages. Abbreviations were applied to represent the studied plots as follows: planted with *S. macrophylla* in the year 1996: SM96; 1997: SM97; 1998: SM98; and 1999: SM99. Study plots sized 20 m × 20 m were established for soil sampling at the adjacent secondary forest (SF; 30 years) outside the rehabilitation areas. For the soil sampling at the rehabilitated areas, soil samples were collected on the planting line of *S. macrophylla* stands at the depth of 0–10 cm (surface soils) and 30–40 cm (subsurface soils) at three random points within each 25 m × 25 m plot in each

stand ages and were mixed well to get a composite sample for each soil layer (Wasli et al., 2009; Perumal et al., 2014, 2015). Similarly, three random points within the 20 m × 20 m plots located outside the rehabilitated sites (SF) were designated for soil sampling, and soils were collected at the depth of 0–10 cm (surface soils) and 30–40 cm (subsurface soils) and mixed well to get a composite sample for each soil layer. Undisturbed soil samples were collected at the depth of 0–10 cm and 30–40 cm using a 100-cc core sampler for the determination of soil physical properties. The general information of each rehabilitation sites and adjacent secondary forest is shown in Table 6.1.

Table 6.1: General information of the study sites; SM96, SM97, SM98, SM99 (rehabilitation sites), and secondary forest (SF).

Study sites	Year planted	Age (years)	GPS location	Species	Planting technique	Number of trees
SM96	1996	18	N01°30'15.0", E109°55'00.3"	<i>S. macrophylla</i>	Line planting	150
SM97	1997	17	N01°30'12.0", E100°54'56.0"	<i>S. macrophylla</i>	Line planting	150
SM98	1998	16	N01°30'12.1", E109°54'54.8"	<i>S. macrophylla</i>	Line planting	150
SM99	1999	15	N01°30'12.1", E109°52'54.3"	<i>S. macrophylla</i>	Line planting	150
SF	Secondary forest	30	N01°30'26.2", E109°58'56.7"	Naturally grown secondary vegetation, pioneer species		

The collected composite soil samples were air-dried for a week, crushed, and homogenised and all the plant materials such as fine roots, leaves, and twigs were carefully removed. Later, the air-dried soil samples were passed through a 2 mm mesh sieve before use for further soil physicochemical analyses.

6.2.3 Methods of Soil Physicochemical Analyses

The detail methods of soil physicochemical analyses were mentioned in Chapter 3 of this study. The soil pH (KCl) was determined in 1M KCl in a soil to solution ratio of 1:5 by glass electrode method. The organic matter (OM) contents in soil was determined using the loss on ignition method (McKeague, 1976; Banning et al., 2008). In addition, the soil particle density was determined using graduated cylinder method (Tan, 2005). All soil physicochemical analyses were conducted at the Laboratory of Environmental Soil Science, Faculty of Resource Science and Technology, Universiti Malaysia Sarawak (UNIMAS).

6.2.4 Methods of Tree Growth Assessment and Survival of *S. macrophylla*

The detail description on the methodology of tree growth assessment and survival of planted *S. macrophylla* were mentioned in Chapter 5 of this study.

6.2.5 Statistical Analyses

All data of soil were expressed on an oven-dry basis. In order to indicate the changes of soil physicochemical properties among the rehabilitated sites in relation to the age of *S. macrophylla* since planting, data on soil physicochemical properties at surface and subsurface soils were statistically analysed and compared using linear regression at 5% and 1% significant levels, respectively. A statistical procedure, Principal Component Analysis (PCA), was used to avoid the redundancy of multivariate data and to determine the most prominent soil parameters which had an influence on the fertility of the soils by integrating the soil physicochemical properties. Integrating PCA score with a soil index which represents a soil fertility status is crucial for estimating the soil fertility and quality in humid tropical forests. In this study, two soil indices, the Soil Fertility Index (SFI) (Moran et al,

2000b) and Soil Evaluation Factor (SEF) (Lu et al., 2002), were used for estimating soil fertility and site quality. Pearson's correlation analysis between the scores on a principal component (PC) as an integrated measure of soil fertility, SFI, or SEF was examined to investigate if the indices can be measures of soil fertility in the rehabilitation sites of Sampadi Forest Reserve. Nonetheless, in this study, Pearson's correlation analysis between the PC score, SFI, and SEF as well as tree growth parameters (diameter at breast height and total height) and survival based on our previous study (Perumal et al., 2015) is performed to elucidate the soil-plant association in order to predict a good indicator for estimating soil fertility and site quality in relation to *S. macrophylla* enrichment planting. All statistical analyses including PCA were performed using IBM SPSS version 21.0 for windows. Lu et al. (2002) reported that the SFI was applied to measuring soil fertility in an Amazonian humid tropical region. On the other hand, significant correlation was found by Moran et al. (2000b) between the SFI, as a measure of quality of Amazonian Ultisols or Oxisols, and the succession rate of the secondary tropical forest. In our previous study (Perumal et al., 2014; 2016), the following equation was used to determine the SFI (Moran et al., 2000b):

$$\text{SFI} = \text{pH} + \text{organic matter (\%, dry soil basis)} + \text{available P (mg kg}^{-1} \text{ dry soil)} + \text{exchangeable K (cmol}_c \text{ kg}^{-1} \text{ dry soil)} + \text{exchangeable Ca (cmol}_c \text{ kg}^{-1} \text{ dry soil)} + \text{exchangeable Mg (cmol}_c \text{ kg}^{-1} \text{ dry soil)} - \text{exchangeable Al (cmol}_c \text{ kg}^{-1} \text{ dry soil)}.$$

However, the SFI may largely depend on pH, but an extremely high pH inhibits plant growth. In addition, pH is not an independent, but a dependent variable of the relative proportion of Ca, Mg, and exchangeable Al concentrations in the soil. A latent drawback of the SFI was pointed out by Lu et al. (2002) since the meaning of SFI is not clear. In order to improve this

drawback, they developed another index, the Soil Evaluation Factor (SEF), for evaluating status of the Amazonian Ultisols and Oxisols. The SEF values were calculated using the following equation in our previous study:

$$\text{SEF} = [\text{exchangeable Ca (cmol}_c \text{ kg}^{-1} \text{ dry soil)} + \text{exchangeable Mg (cmol}_c \text{ kg}^{-1} \text{ dry soil)} + \text{exchangeable K (cmol}_c \text{ kg}^{-1} \text{ dry soil)} - \log (1 + \text{exchangeable Al (cmol}_c \text{ kg}^{-1} \text{ dry soil}))] \times \text{organic matter (\%, dry soil basis)} + 5.$$

6.3 Results and Discussion

6.3.1 Soil Physicochemical Properties under Various Stand Ages of Rehabilitation

Sites and Secondary Forest at Sampadi Forest Reserve, Lundu, Sarawak

The mean values of soil physicochemical properties of rehabilitation sites (SM96, SM97, SM98, and SM99) and adjacent secondary forest (SF) are presented in Tables 6.2 and 6.3. In general, the soil texture did not vary widely in all the study sites, where most soils were relatively sandy, ranging from sandy clay loam to sandy clay in texture. The content of sand in surface and subsurface soils was fewer than 56%, while that of clay content was above 29%. The clay contents in surface and subsurface soils were 29.0 to 45.9% and 31.2 to 48.1%, respectively. On the other hand, the sand content in surface and subsurface soils ranged from 29.3 to 53.7% and 31.4 to 55.2%, respectively. Comparatively, soil organic matter (SOM) in surface soils was relatively higher than that of the subsurface soils. The SOM mean values at the surface and subsurface soils ranged from 6.63 to 9.30% and 3.88 to 5.97%, respectively. The mean SOM for the secondary forest (SF) presented higher value in comparison to that of the rehabilitation sites (SM96, SM97, SM98, and SM99).

Soils of all the study sites in Sampadi Forest Reserve could be characterised as strongly acidic, with pH (H₂O) values of less than 5.50 (ranging from 4.67 to 5.29 and 5.01 to 5.38) at both surface and subsurface soil layers, respectively. The soil pH (KCl) of all study sites was moderately acidic at pH less than 4.50 (ranging from 3.63 to 4.31 and 3.72 to 4.48) at both surface and subsurface soil layers, respectively. On the other hand, the soil electrical conductivity at the surface and subsurface soil ranged from 120.0 to 193.6 $\mu\text{S cm}^{-1}$ and 47.5 to 132.9 $\mu\text{S cm}^{-1}$, respectively. In terms of soil total carbon (Total C) and total nitrogen (Total N), the soils in this study had higher values in surface soils than in subsurface soils. The soil Total C value for surface soil ranged from 38.5 to 53.9 g kg⁻¹ and that for subsurface soil ranged from 22.6 to 34.6 g kg⁻¹. At the depth of 0–10 cm, the Total N level of soil ranged from 2.16 to 3.05 g kg⁻¹, whereas at the depth of 30–40 cm, it ranged from 0.95 to 1.61 g kg⁻¹. Generally, the contents of Total C and Total N in secondary forest (SF) were higher than that of the rehabilitation sites. Among the five study sites, secondary forest showed the highest level of Total C and Total N at both surface and subsurface soils, which leads to the lower value of C/N ratio as compared to other study sites except in SM99. In spite of high Total C and Total N contents in the secondary forest (SF), no clear difference was detected for C/N ratio in rehabilitation sites and secondary forest (SF).

In general, the soil cation exchange capacity (CEC) value was low for the surface and subsurface soils for all the rehabilitation sites and secondary forest. The CEC value ranged from 8.4 to 11.8 cmol_c kg⁻¹ in surface soils and ranged from 7.0 to 9.3 cmol_c kg⁻¹ in subsurface soils. For surface soils, the highest value was from SM96 (11.8 cmol_c kg⁻¹), while the lowest value was from SM99 (8.4 cmol_c kg⁻¹). On the other hand, as for the subsurface soils, the highest CEC was from the secondary forest (SF) (9.3 cmol_c kg⁻¹) and the lowest was from SM98 (7.0 cmol_c kg⁻¹).

Throughout the sites, soil exchangeable cations (Ca, Mg, and K) in surface soils were found higher as compared to the subsurface soils. The soil exchangeable Ca at surface and subsurface soils ranged from 0.26 to 0.68 $\text{cmol}_c \text{ kg}^{-1}$ and 0.02 to 0.43 $\text{cmol}_c \text{ kg}^{-1}$, respectively. The exchangeable Mg ranged from 0.24 to 0.38 $\text{cmol}_c \text{ kg}^{-1}$ at surface soils and ranged from 0.11 to 0.15 $\text{cmol}_c \text{ kg}^{-1}$ at subsurface soils. The exchangeable K ranged from 0.12 to 0.32 $\text{cmol}_c \text{ kg}^{-1}$ at surface soils and ranged from 0.06 to 0.25 $\text{cmol}_c \text{ kg}^{-1}$ at subsurface soils. In comparison to soil exchangeable Al, the exchangeable bases in surface and subsurface soils were low, resulting in a high level of Al saturation at rehabilitation sites as well as secondary forest. Al saturation was depicted above 40% at surface soils and more than 60% at subsurface soils. Comparatively, the soil exchangeable Al in subsurface soils was greater than the surface soils for rehabilitation sites and secondary forest except for SM98 whereby the soil exchangeable Al contents were greater in surface soils as compared to the subsurface soils. However, in SM99, the soil exchangeable Al content was the same for surface and subsurface soils. At the depth of 0–10 cm, the soil exchangeable Al ranged from 1.35 to 4.03 $\text{cmol}_c \text{ kg}^{-1}$ and ranged from 1.30 to 4.30 $\text{cmol}_c \text{ kg}^{-1}$ at the depth of 30–40 cm.

The values of soil available P in surface and subsurface soils ranged from 2.4 to 14.0 mg P kg^{-1} and 0.9 to 5.9 mg P kg^{-1} , respectively. The mean soil bulk density of subsurface soils was higher than that of surface soils. The soil bulk density at the depth of 0–10 cm ranged from 0.90 to 1.08 g mL^{-1} and at the depth of 30–40 cm ranged from 1.11 to 1.36 g mL^{-1} . Secondary forest (SF) had the lowest soil bulk density value (0.90 g mL^{-1}) as compared to that of the rehabilitation sites and SM96 had the highest soil bulk density value (1.08 g mL^{-1}) at surface soils.

Table 6.2: Means and standard deviation of surface soil physicochemical properties at rehabilitation sites (SM96, SM97, SM98, and SM99) and secondary forest (SF).

Age-since-planting/ Soil physicochemical properties	Rehabilitation sites				Secondary forest
	SM96 (18 years)	SM97 (17 years)	SM98 (16 years)	SM99 (15 years)	SF (30 years)
<u>Surface soil, 0-10 cm depth</u>					
pH(H ₂ O)**	4.69 ± 0.12	4.67 ± 0.09	4.72 ± 0.08	5.20 ± 0.06	5.29 ± 0.26
pH(KCl)**	3.92 ± 0.08	3.63 ± 0.56	4.07 ± 0.05	4.31 ± 0.07	4.16 ± 0.15
EC ^{a**} (μS cm ⁻¹)	120.0 ± 13.3	163.2 ± 32.9	165.7 ± 51.0	193.6 ± 10.6	188.2 ± 25.2
SOM ^b (%)	6.63 ± 1.71	8.54 ± 1.51	8.91 ± 2.06	8.52 ± 0.83	9.30 ± 1.40
Total C ^c (g kg ⁻¹)	38.5 ± 9.9	49.6 ± 8.8	51.7 ± 12.0	49.4 ± 4.8	53.9 ± 8.1
Total N ^d (g kg ⁻¹)	2.16 ± 0.67	2.55 ± 0.38	2.99 ± 1.01	2.91 ± 0.80	3.05 ± 0.50
C/N ratio	18.27 ± 2.89	19.54 ± 3.00	18.22 ± 4.55	17.74 ± 3.46	17.78 ± 1.43
CEC ^{e*} (cmol _c kg ⁻¹)	11.8 ± 2.8	9.7 ± 1.6	9.5 ± 1.6	8.4 ± 3.0	10.2 ± 1.2
Exch. Ca ²⁺ (cmol _c kg ⁻¹)	0.52 ± 0.17	0.48 ± 0.25	0.68 ± 0.25	0.26 ± 0.28	0.54 ± 0.43
Exch. Mg ²⁺ (cmol _c kg ⁻¹)	0.33 ± 0.07	0.35 ± 0.17	0.24 ± 0.09	0.30 ± 0.04	0.38 ± 0.20
Exch. K ⁺ * (cmol _c kg ⁻¹)	0.15 ± 0.04	0.12 ± 0.02	0.18 ± 0.03	0.17 ± 0.03	0.32 ± 0.03
Exch. Al ^{3+***} (cmol _c kg ⁻¹)	2.54 ± 0.82	4.03 ± 0.40	1.35 ± 0.19	1.56 ± 0.24	1.40 ± 0.41
SUM ^{f**} (cmol _c kg ⁻¹)	1.45 ± 0.23	1.35 ± 0.42	1.36 ± 0.35	0.84 ± 0.32	1.77 ± 0.62
ECEC ^{g**} (cmol _c kg ⁻¹)	3.99 ± 1.01	5.38 ± 0.40	2.71 ± 0.51	2.40 ± 0.44	3.16 ± 0.65
Base saturation (%)	12.6 ± 2.3	14.3 ± 4.8	14.1 ± 1.6	11.5 ± 6.4	17.2 ± 5.5
Available P ^{**} (mg P kg ⁻¹)	14.0 ± 2.1	13.6 ± 1.5	6.3 ± 1.0	2.4 ± 1.1	5.5 ± 1.2
Al saturation (%)	62.9 ± 5.1	75.0 ± 6.7	50.4 ± 4.4	65.8 ± 7.6	44.5 ± 13.6

Values in the same row indicate means ± standard deviation, ^a EC: Electrical Conductivity, ^b SOM; Soil Organic Matter, ^c Total C: Total Carbon; ^d Total N: Total Nitrogen; ^e CEC: Cation Exchange Capacity; ^f Sum of Exchangeable Bases (Ca, Mg, K, Na), ^g ECEC; Effective CEC, sum of exchangeable bases and exchangeable Al. *, ** Correlations are significant at 5% and 1% levels, respectively among the rehabilitation sites.

Table 6.2 continued

Age-since-planting/ Soil physicochemical properties		Rehabilitation sites				Secondary forest
		SM96 (18 years)	SM97 (17 years)	SM98 (16 years)	SM99 (15 years)	SF (30 years)
<u>Surface soil, 0-10 cm depth</u>						
Clay**	(%)	29.0 ± 8.8	36.9 ± 5.8	41.2 ± 7.2	40.3 ± 6.7	45.9 ± 1.9
Silt**	(%)	21.8 ± 5.9	33.8 ± 4.2	5.1 ± 2.7	6.8 ± 3.3	6.4 ± 2.1
Sand	(%)	49.1 ± 11.9	29.3 ± 7.1	53.7 ± 7.4	53.0 ± 9.1	47.7 ± 2.6
Bulk density	(g mL ⁻¹)	1.08 ± 0.07	0.92 ± 0.13	1.01 ± 0.09	0.93 ± 0.08	0.90 ± 0.04
Particle density	(g mL ⁻¹)	2.52 ± 0.16	2.49 ± 0.15	2.32 ± 0.18	2.83 ± 0.65	2.42 ± 0.09
Moisture content	(%)	3.0 ± 0.9	4.4 ± 0.5	3.6 ± 0.5	4.0 ± 0.7	4.0 ± 0.2

*, ** Correlations are significant at 5% and 1% levels, respectively among the rehabilitation sites.

Table 6.3: Means and standard deviation of subsurface soil physicochemical properties at rehabilitation sites (SM96, SM97, SM98, and SM99) and secondary forest (SF).

Age-since-planting/ Soil physicochemical properties	Rehabilitation sites				Secondary forest
	SM96 (18 years)	SM97 (17 years)	SM98 (16 years)	SM99 (15 years)	SF (30 years)
<u>Subsurface soil, 30-40 cm depth</u>					
pH(H ₂ O)**	5.01 ± 0.05	5.04 ± 0.05	5.35 ± 0.16	5.29 ± 0.05	5.38 ± 0.05
pH(KCl)**	3.91 ± 0.06	3.72 ± 0.04	4.27 ± 0.05	4.33 ± 0.06	4.48 ± 0.05
EC ^{a**} (μS cm ⁻¹)	52.7 ± 7.0	54.6 ± 2.9	47.5 ± 7.9	122.3 ± 1.9	132.9 ± 13.3
SOM ^b (%)	3.88 ± 0.90	4.03 ± 0.74	4.44 ± 0.85	4.70 ± 0.84	5.97 ± 0.89
Total C ^c (g kg ⁻¹)	22.6 ± 5.2	23.4 ± 4.3	25.8 ± 4.9	27.3 ± 4.9	34.6 ± 5.1
Total N ^{d*} (g kg ⁻¹)	0.95 ± 0.44	1.06 ± 0.17	1.07 ± 0.29	1.34 ± 0.30	1.61 ± 0.41
C/N ratio	26.25 ± 8.03	22.10 ± 3.40	24.70 ± 3.97	20.62 ± 3.28	22.00 ± 2.95
CEC ^e (cmol _c kg ⁻¹)	7.8 ± 2.3	7.3 ± 1.4	7.0 ± 1.4	7.7 ± 1.7	9.3 ± 0.9
Exch. Ca ²⁺ (cmol _c kg ⁻¹)	0.13 ± 0.05	0.17 ± 0.07	0.43 ± 0.19	0.02 ± 0.02	0.07 ± 0.05
Exch. Mg ²⁺ (cmol _c kg ⁻¹)	0.12 ± 0.04	0.15 ± 0.10	0.11 ± 0.07	0.11 ± 0.01	0.14 ± 0.07
Exch. K ⁺ ** (cmol _c kg ⁻¹)	0.06 ± 0.02	0.06 ± 0.01	0.08 ± 0.02	0.11 ± 0.02	0.25 ± 0.06
Exch. Al ³⁺ ** (cmol _c kg ⁻¹)	2.72 ± 1.18	4.30 ± 0.66	1.30 ± 0.30	1.56 ± 0.17	1.81 ± 0.23
SUM ^f (cmol _c kg ⁻¹)	0.65 ± 0.19	0.76 ± 0.16	0.86 ± 0.30	0.32 ± 0.04	0.89 ± 0.30
ECEC ^{g**} (cmol _c kg ⁻¹)	3.37 ± 1.33	5.06 ± 0.76	2.16 ± 0.44	1.88 ± 0.16	2.69 ± 0.38
Base saturation (%)	8.6 ± 2.4	10.4 ± 1.5	12.6 ± 4.1	4.3 ± 0.9	9.5 ± 3.0
Available P** (mg P kg ⁻¹)	5.9 ± 1.5	3.7 ± 0.4	2.6 ± 1.3	3.3 ± 1.9	0.9 ± 0.3
Al saturation (%)	79.0 ± 7.6	85.0 ± 2.3	60.5 ± 9.4	82.9 ± 3.0	67.6 ± 8.9

Values in the same row indicate means ± standard deviation, ^a EC: Electrical Conductivity, ^b SOM; Soil Organic Matter, ^c Total C: Total Carbon; ^d Total N: Total Nitrogen; ^e CEC: Cation Exchange Capacity; ^f Sum of Exchangeable Bases (Ca, Mg, K, Na), ^g ECEC; Effective CEC, sum of exchangeable bases and exchangeable Al. *, ** Correlations are significant at 5% and 1% levels, respectively among the rehabilitation sites.

Table 6.3 continued

Age-since-planting/ Soil physicochemical properties		Rehabilitation sites				Secondary forest
		SM96 (18 years)	SM97 (17 years)	SM98 (16 years)	SM99 (15 years)	SF (30 years)
<u>Subsurface soil, 30-40 cm depth</u>						
Clay	(%)	31.2 ± 6.9	37.7 ± 6.4	36.1 ± 8.6	36.5 ± 5.8	48.1 ± 2.5
Silt**	(%)	25.8 ± 5.8	30.9 ± 2.8	8.7 ± 7.5	8.7 ± 3.5	4.9 ± 1.1
Sand**	(%)	43.0 ± 7.0	31.4 ± 8.7	55.2 ± 13.2	54.9 ± 3.8	47.0 ± 2.9
Bulk density	(g mL ⁻¹)	1.32 ± 0.14	1.11 ± 0.04	1.36 ± 0.12	1.35 ± 0.18	1.13 ± 0.19
Particle density	(g mL ⁻¹)	2.50 ± 0.15	2.53 ± 0.09	2.40 ± 0.14	2.68 ± 0.14	2.62 ± 0.27
Moisture content	(%)	2.6 ± 0.9	3.7 ± 0.7	2.8 ± 0.6	3.3 ± 0.7	3.7 ± 0.4

*, ** Correlations are significant at 5% and 1% levels, respectively among the rehabilitation sites.

At subsurface soils, SM97 depicted the lowest value in soil bulk density (1.11 g mL^{-1}) and SM98 depicted the highest value in soil bulk density (1.36 g mL^{-1}).

6.3.2 Soil Texture, Organic Matter, and Cation Exchange Capacity-Related Properties

The fertility of tropical soils is mainly dependent on the negative charges derived from clay content and organic matter under the acidic nature of the soils (Arifin et al., 2007; Tanaka et al., 2007, 2009). In the present study, a high positive correlation was observed between Total C and clay contents in both the surface soils and subsurface soils: $r = 0.832^{**}$ and $r = 0.880^{**}$ (data not shown), respectively. This indicated that they are ascribable to soil organic matter stabilisation by the stable organomineral complexes formation (Ohta et al., 2000; Tanaka et al., 2007). However, the results of standardized multiple regression analysis showed no correlation between CEC values and either Total C or clay contents in either surface ($\text{CEC} = 0.211 \text{ Total C} - 0.057 \text{ clay}$ ($r = 0.167$)) or subsurface soils ($\text{CEC} = 0.504 \text{ Total C} + 0.199 \text{ clay}$ ($r = 0.686$)). The fact that the CEC was higher as compared to the effective cation exchange capacity (ECEC) suggested the possible existence of certain variable negative charges (Boonyanuphap et al., 2007; Tanaka et al., 2009). Since the ECEC values were much lower than the CEC values, permanent negative charges of clay minerals were predominant under acidic conditions. The small difference between soil CEC and ECEC suggested low input of negative charges from soil organic matter to the cation retention capacity (Arifin et al., 2008). Although the content of soil total carbon was significantly higher in secondary forest than rehabilitation sites, there was no large difference between the rehabilitation sites and secondary forest for soil total carbon, total nitrogen, or clay contents. It is notable that the negative charges derived from clay content and organic matter are considered as a

significant factor for nutrient retention capacity and possibly influence the fertility status of soils to a certain extent (Hamzah et al., 2009). In addition, the soil Total C, Total N, and CEC values are also likely to be affected by the input-output balance of soil organic matter after the period of establishment of the rehabilitation sites and in the fallow period of the secondary forest through inputs of litterfall and output by decomposition.

According to Akbar et al. (2010), organic matter from the soil gradually decreased after harvesting or clearing of forest due to the loss of organic matter source from the plant. Nevertheless, similar studies by Nye and Greenland (1964), Kendawang et al. (2004), and Ilstedt et al. (2004) mentioned that the soil organic matter decreases rapidly after the soil was exposed to land clearing or harvesting activities. A study by Ishizuka et al. (1998) reported that the soil organic matter content was high in the surface layers due to the accumulation of forest litter and the development of root mats in the soil. Similar findings revealed in the present study whereby the soil organic matter values in surface soils were generally higher as compared to the subsurface soils. The higher content of soil Total C especially in the secondary forest was likely due to a large input and greater accumulation of fresh organic matter in soils from the existing vegetation in the former than the latter.

6.3.3 Soil Acidity and Exchangeable Bases-Related Properties

According to Juo and Manu (1996), the loss of soil exchangeable bases via uptake by vegetation and leaching in the tropical environment as well as volatilization during combustion had caused soils being acidic in nature, especially in the reforestation sites (Giardina et al., 2000). In addition, Tan (2005) reported that, for soil pH below 6.0, some available nutrients are poor. The formation of clay minerals and microbial activity including soil characteristics and processes are influenced by the soil pH. In the present study,

especially in SM96 and SM97 rehabilitation sites, the soil pH for both surface and subsurface soils was more acidic as compared to the secondary forest due to the occurrence of high soil exchangeable Al. The presence of a large amount of aluminium and hydrogen ions in the soils resulted in the acidity of forest soils. In addition, Zaidey et al. (2010) stated that the soil organic matter content and Al concentrations probably contributed to the soil acidity. Although aluminium is not useful for plant growth and not deliberated as a plant nutrient, it could be used as an indicator for weathering status and acidity of the soils. Akbar et al. (2010) mentioned that Al toxicity will disturb and restrict the growth of seedling and the acidity presumably caused by water deficiency during drought season. Accumulation of forest litter and development of root mats on the surface layer of soil may result in high carbon content, which may indirectly affect the acidity of the soil. Nonetheless, Etsuko et al. (2004) reported that higher amount of calcium corresponds to the higher pH value. Association of biological accumulation through the supply of forest litter and their lower mobility in soil caused higher contents of soil exchangeable Ca and Mg in surface soils (Ohta et al., 1993; Soto & Diaz-Fierros, 1993). During heavy rainfall season, the exchangeable K from the decomposition of dead plants probably dissolved easily into the deep layer of soil. In addition, Ohta and Effendi (1992) described that subsurface soil may play a vital role as a nutrient storage whereby some available nutrients in the subsurface layer are pumped up and transferred gradually to the surface soil.

6.3.4 Identification of Intrinsic Soil Properties in relation to Soil Fertility at Rehabilitation Sites

Principal Component Analysis (PCA) is a multivariate data analysis used to analyse set of soil physicochemical properties to reduce the original complicated dimensionality and to

give a few principal components (PC score) that explain the variation in the data (Arifin et al., 2008). In the present study, PCA was performed for the rehabilitated sites (SM96, SM97, SM98, and SM99) by using 13 selected variables related to the surface and subsurface soil physicochemical properties in order to determine the important variables that affect the soil fertility at the study sites as shown in Table 6.4.

The PCA results generated three most significant PC scores (PC1, PC2, and PC3), which described approximately 76.3% of the total variability and each component portrays a series of variables which simplifies the analysis and interpretation. The first component score (PC1) represents intrinsic properties of the soil related to available phosphorus, soil acidity (exchangeable Al), and soil texture (silt) which exhibited high positive factor loadings, while pH (H₂O) and sand content exhibited high negative factor loadings for surface soils. The second principal component (PC2) showed a high positive factor loading for total nitrogen, clay content, and soil organic matter, whereas a high negative factor loading for bulk density reflects soil organic matter constituent at surface soils. Meanwhile, at subsurface soils, the first principal component (PC1) was related to soil acidity and soil texture as exchangeable Al and silt content showed high positive factor loadings, while pH (H₂O), sand content, and bulk density showed high negative factor loadings (Table 6.4). On the other hand, PC2 for subsurface soils showed a high positive factor loading for total nitrogen, exchangeable K, clay content, and bulk density reflecting the cation retention capacity and soil organic matter constituent. The third principal component (PC3) at subsurface soils was related to available nutrient as exchangeable Ca showed a high negative factor loading. Thus, based on the results obtained, this indicated that the PCA produces the ability of the three principal component scores to integrate soil physicochemical characteristics within the components.

Table 6.4: Factor loadings of surface and subsurface soil physicochemical properties, principal component analysis (PCA), and results of PCA of the rehabilitated forest.

		Variables analysed		
		pH (H ₂ O), SOM, Total N, CEC, Exch. Ca, Exch. Mg, Exch. K, Exch. Al, Available P, Clay, Silt, Sand contents, and Bulk density		
	Value	PC1	PC2	PC3
<u>Surface soils (0-10 cm)</u>				
Contribution ratio (%)		34.4	29.2	12.7
Variables with a high positive factor loading (> 0.7)	+	Exch. Al, Available P and Silt	Total N, Clay and SOM	ND
Variables with a high negative factor loading (> 0.7)	-	pH (H ₂ O) and Sand	Bulk density	ND
Contribution name of PC axis		Available phosphorus, soil acidity and soil texture	Soil organic matter constituent	

(+) = Factor loading with a positive value; (-) = Factor loading with a negative value; and ND = Not Determined. SOM = Soil organic matter, Total N = Total nitrogen, Exch. Ca, Mg, K and Al = Exchangeable Ca, Mg, K, and Al, Clay, Silt, and Sand = percentage of clay, silt, and sand.

Table 6.4 continued

		Variables analysed		
		pH (H ₂ O), SOM, Total N, CEC, Exch. Ca, Exch. Mg, Exch. K, Exch. Al, Available P, Clay, Silt, Sand contents, and Bulk density		
	Value	PC1	PC2	PC3
<u>Subsurface soils (30-40 cm)</u>				
Contribution ratio (%)		34.4	29.3	10.3
Variables with a high positive factor loading (> 0.7)	+	Exch. Al and Silt	Total N, Exch. K, Clay and SOM	ND
Variables with a high negative factor loading (> 0.7)	-	pH (H ₂ O), Sand and Bulk density	ND	Exch. Ca
Contribution name of PC axis		Soil acidity and soil texture	Cation retention capacity, soil organic matter constituent	Available nutrient

(+) = Factor loading with a positive value; (-) = Factor loading with a negative value; and ND = Not Determined. SOM = Soil organic matter, Total N = Total nitrogen, Exch. Ca, Mg, K and Al = Exchangeable Ca, Mg, K, and Al, Clay, Silt, and Sand = percentage of clay, silt, and sand.

In addition, the information derived from PCA can be applied to the development of basic indicators which can be used to explain the more complex variability of soil physicochemical properties.

Figure 6.1 shows the correlation between PC1 and PC2 scores from PCA in the study sites for surface soils. Based on the correlation in the study sites for surface soils, clear differences were observed for several soil properties which categorised into phosphorus content, soil acidity, and soil texture. Hence, the available phosphorus of the soil was one of the determining factors which influenced the growth of the planted *S. macrophylla* in the study sites. In addition, no clear tendency was shown for soil acidity and soil texture related to PC1. Based on PCA, since subsurface soil properties showed similar but fewer tendencies than those of the surface soils, the intrinsic results of surface soils properties will be chiefly used for further discussion.

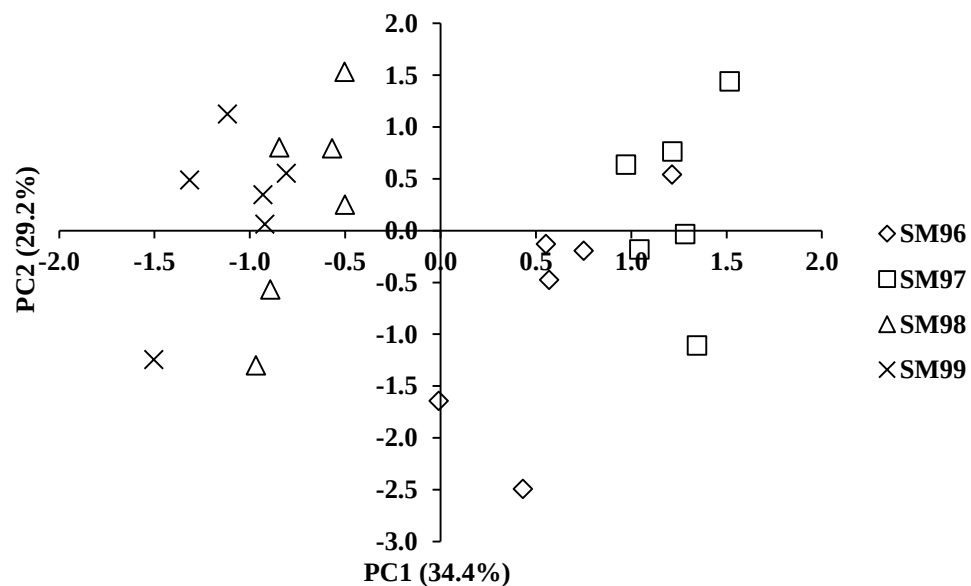


Figure 6.1: Correlation between PC1 and PC2 scores from Principal Component Analysis (PCA) in the study sites for surface soils.

The first component score, PC1 from PCA, will be used for the discussion since it shows the highest contribution ratio (34.4%) as compared to PC2 (29.2%) and PC3 (12.7%).

6.3.5 Relationship between Soil Fertility and Growth Performance of Planted *S. macrophylla* at Different Stand Ages with Special Reference to PC Score, SFI, and SEF

The suitable procedure to assess the soil conditions in the tropical rainforests was found to be difficult due to the variations of soil properties. In forest management, the evaluation of soil fertility status and site quality is essential since it reflects the productive capacity of the forest area to support the growth of plants (Lu et al, 2002; Arifin et al., 2008). Moran et al. (2000b) stated that a Soil Fertility Index (SFI) was employed to investigate the relationship between soil fertility and secondary forests succession rate as well as vegetation selection, while the Soil Evaluation Factor (SEF) was used to evaluate soil fertility with different soil types (Lu et al., 2002). Originally, the Soil Fertility Index (SFI) was developed as a measure of fertility of soils for cacao production (Alvim & Rosand, 1974). In the Amazonian humid tropical forests of Brazil, both of these soil indices were used to predict the increase in aboveground biomass and to evaluate soil fertility and site productivity under various stages of tropical secondary forests succession. Furthermore, in Northern Thailand, studies have proven that SFI and SEF have been used for soil quality and productivity along a gradient of land degradation (Doi & Sakurai, 2004). However, less attention has been paid to the applicability of using these soil indices for estimating soil fertility and site quality in secondary forests undergoing rehabilitation especially by using indigenous species (Arifin et al., 2008) (dipterocarp species such as *S. macrophylla*), as for the case in this study. In order to investigate if any of the proposed index for estimating soil quality is applicable to

the soils in Sampadi Forest Reserve, as well as for the association between the soil fertility status and productivity of planted *S. macrophylla* after enrichment planting, correlations between the PCA score and the values of Soil Fertility Index (SFI) (Moran et al., 2000b) and Soil Evaluation Factor (SEF) (Lu et al., 2002) were determined.

Thus, the SFI and SEF were employed for the rehabilitation sites in the present study since both indices are applicable for estimating soil fertility under vegetation succession of secondary forest in humid tropical regions of Brazil (Moran et al, 2000b; Lu et al., 2002). A principal component analysis showed the most important PC scores and revealed the significant soil properties which contribute to the soil fertility under rehabilitation (Table 6.4). The values of Soil Fertility Index (SFI) and Soil Evaluation Factor (SEF) for rehabilitation sites and secondary forest (SF) for surface soils (0–10 cm) and subsurface soils (30–40 cm) were clearly explained in our previous study (Perumal et al., 2014, 2016). The relationship between PC1 score and SFI and between the PC1 score and the SEF is shown in Figure 6.2. Based on Figure 6.2, there was a high positive correlation between the PC1 score and SFI at surface soils ($r = 0.789^{**}$, $P < 0.01$) but no correlation was found at subsurface soils. On the other hand, no correlation was found between the PC1 score and SEF for both surface and subsurface soils. Hence, the results revealed that SFI showed similarity factors with the PC1 score, indicating the applicability of SFI as an index which can be used for estimating soil fertility status in the present study.

Nonetheless, in order to determine the applicability of these indices for estimating soil fertility and site quality in relation to survivorship and growth performance of planted *S. macrophylla* after enrichment planting, the values of the PC1 score, SFI, and SEF at both surface and subsurface soil depths were further correlated with the tree growth parameters (diameter at breast height (DBH) and height) and survival of the planted *S. macrophylla* trees

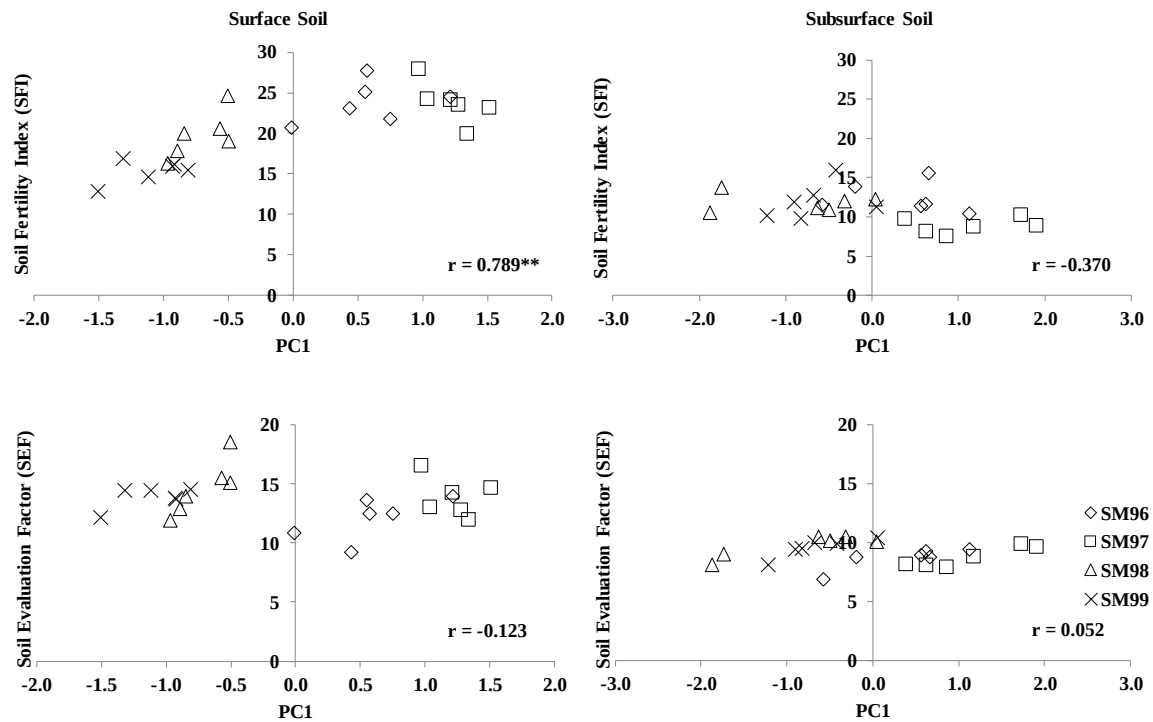


Figure 6.2: Relationship between PC1 score derived from PCA analysis and the calculated Soil Fertility Index (SFI) and Soil Evaluation Factor (SEF) for surface and subsurface soils. ** Correlations are significant at 1% level, using Pearson correlation matrix.

from our previous study (Perumal et al., 2017a). The results revealed positive and moderate correlations between the PC1 score and diameter at breast height (DBH) and survival percentage at surface soils ($r = 0.546^{**}$, $P < 0.01$ and $r = 0.477^{*}$, $P < 0.05$, respectively) as shown in Figure 6.3. On the other hand, there was no correlation observed between PC1 score and the tree height of *S. macrophylla* at both surface and subsurface soils. Meanwhile, at subsurface soils, there was a positive correlation obtained between PC1 score and diameter at breast height ($r = 0.437^{*}$, $P < 0.05$). However, no correlation was found between the PC1 score and the survival percentage of the trees at subsurface soils (Figure 6.3). Based on Table 6.5, the results indicated that there were high significant correlations between SFI and DBH, height, and percentage of survival at surface soils. The Pearson's correlation between the SFI and DBH, height, and percentage of survival ranged from 0.483 to 0.684.

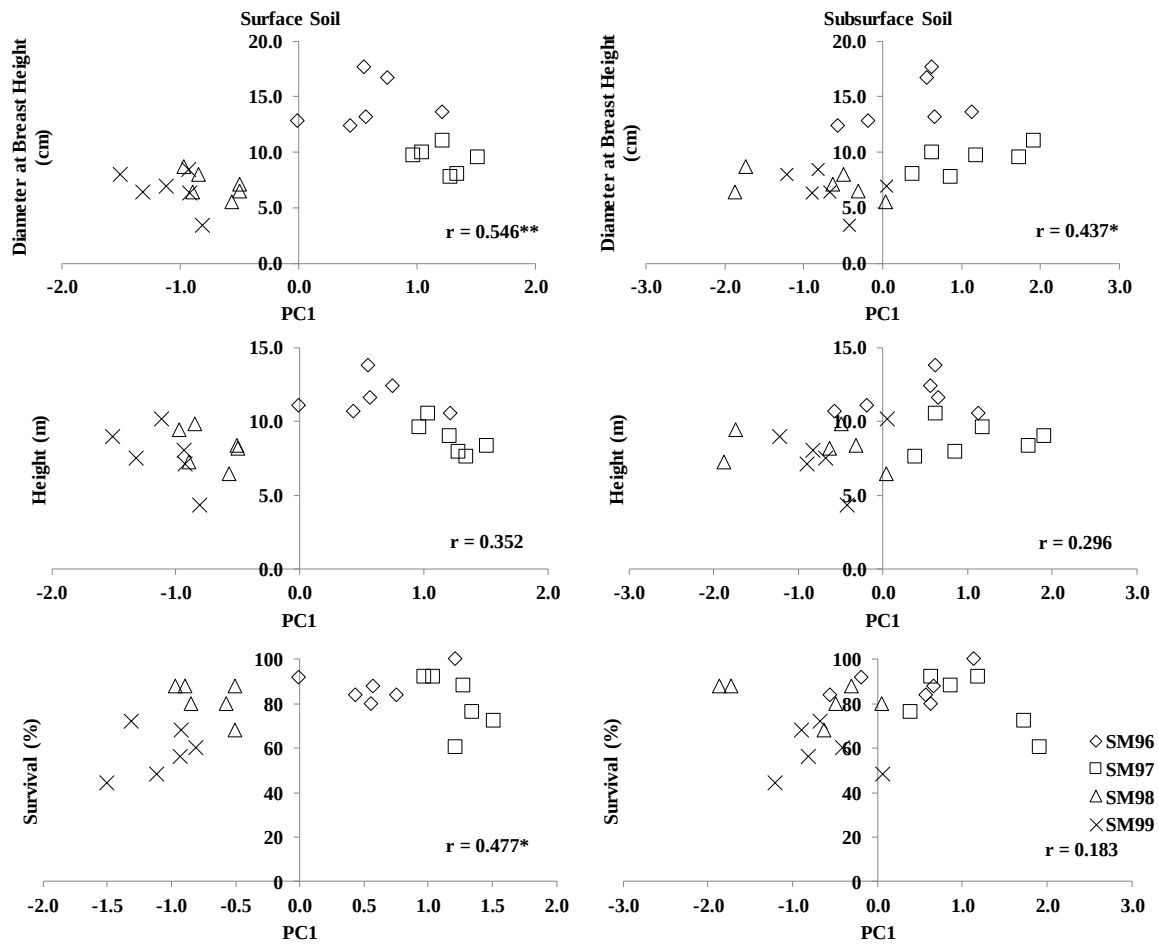


Figure 6.3: Relationship between PC1 score, diameter at breast height (DBH), height, and percentage of survival derived from surface and subsurface soils. *, ** Correlations are significant at 5% and 1% levels, respectively, using Pearson correlation matrix.

The SFI was correlated with DBH ($r = 0.565^{**}$, $P < 0.01$), height ($r = 0.483^{*}$, $P < 0.05$), and survival ($r = 0.684^{**}$, $P < 0.01$) at surface soils, whereas no significant correlations were found at subsurface soils for SFI (Figure 6.4). Moreover, there were no significant correlations observed between SEF and DBH, height, and survival percentage for both surface and subsurface soils as shown in Figure 6.5. Hence, these results showed that the SFI is also one of the applicable indices to determine soil fertility status as well as site quality in relation to the productivity of *S. macrophylla* planting in this study. Arifin et al. (2008) mentioned that SEF might not be appropriate for sandy textured soils such as in the present

study since the level of soil exchangeable cations was relatively lower than that of soil exchangeable Al. A brief summary of the relationship between PC1 score, SFI, SEF, and tree growth parameters (diameter at breast height (DBH) and height) and percentage of survival was shown in Table 6.6.

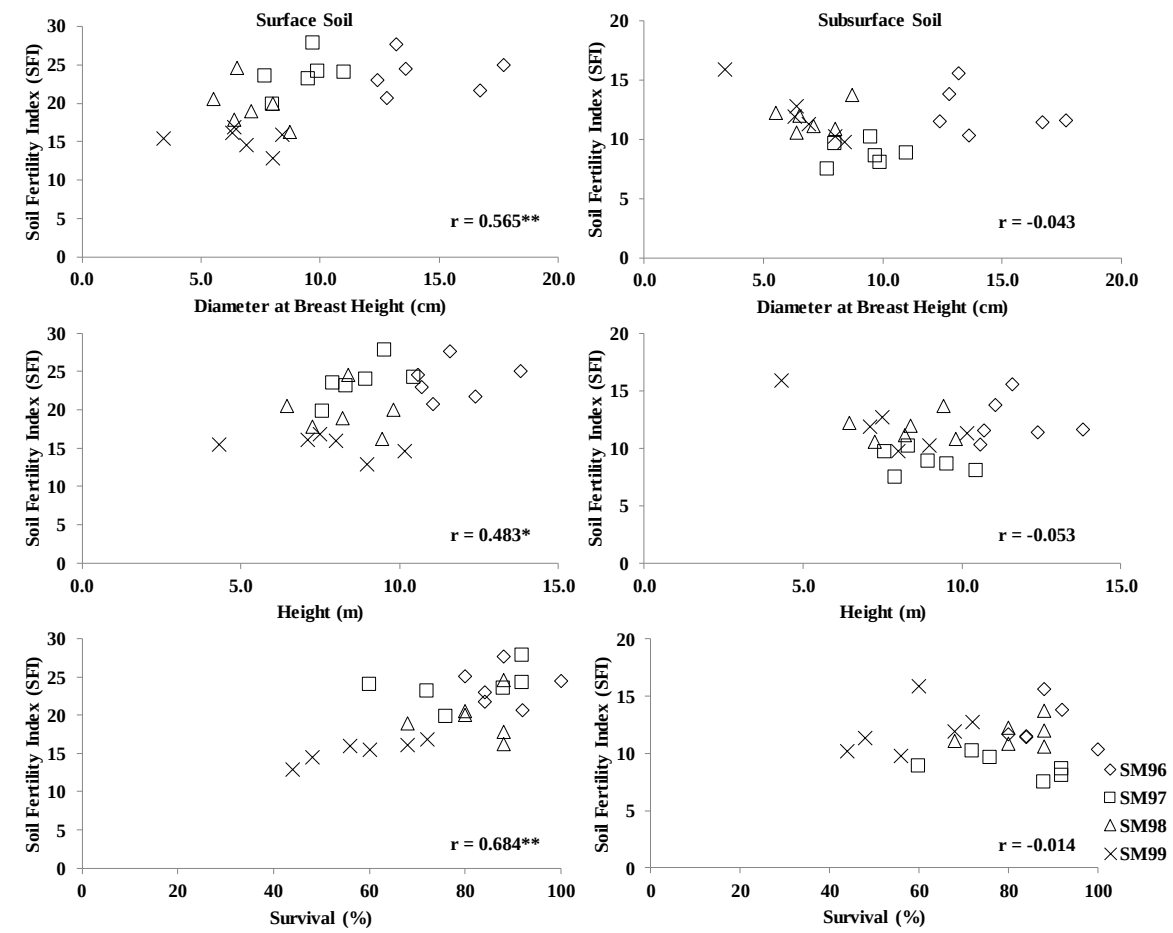


Figure 6.4: Relationship between diameter at breast height (DBH), height, and percentage of survival with Soil Fertility Index (SFI) derived from surface and subsurface soils. *, ** Correlations are significant at 5% and 1% levels, respectively, using Pearson correlation matrix.

In order to predict the best indicator for estimating soil fertility and site quality in relation to survivorship and growth performance of planted *S. macrophylla* after enrichment planting, the values of soil available phosphorus content at the rehabilitation sites for both

surface and subsurface soil depths were correlated with tree growth parameters (diameter at breast height (DBH) and height) and survival from our previous study (Perumal et al., 2017a). The results indicated that there was a strong relationship between the soil available phosphorus and tree growth parameters: diameter at breast height, height, and percentage of survival as shown in Figure 6.6. There were strong and moderate positive correlations between the soil available phosphorus and diameter at breast height at surface soils ($r = 0.678^{**}$, $P < 0.01$) and subsurface soils ($r = 0.454^*$, $P < 0.05$), respectively.

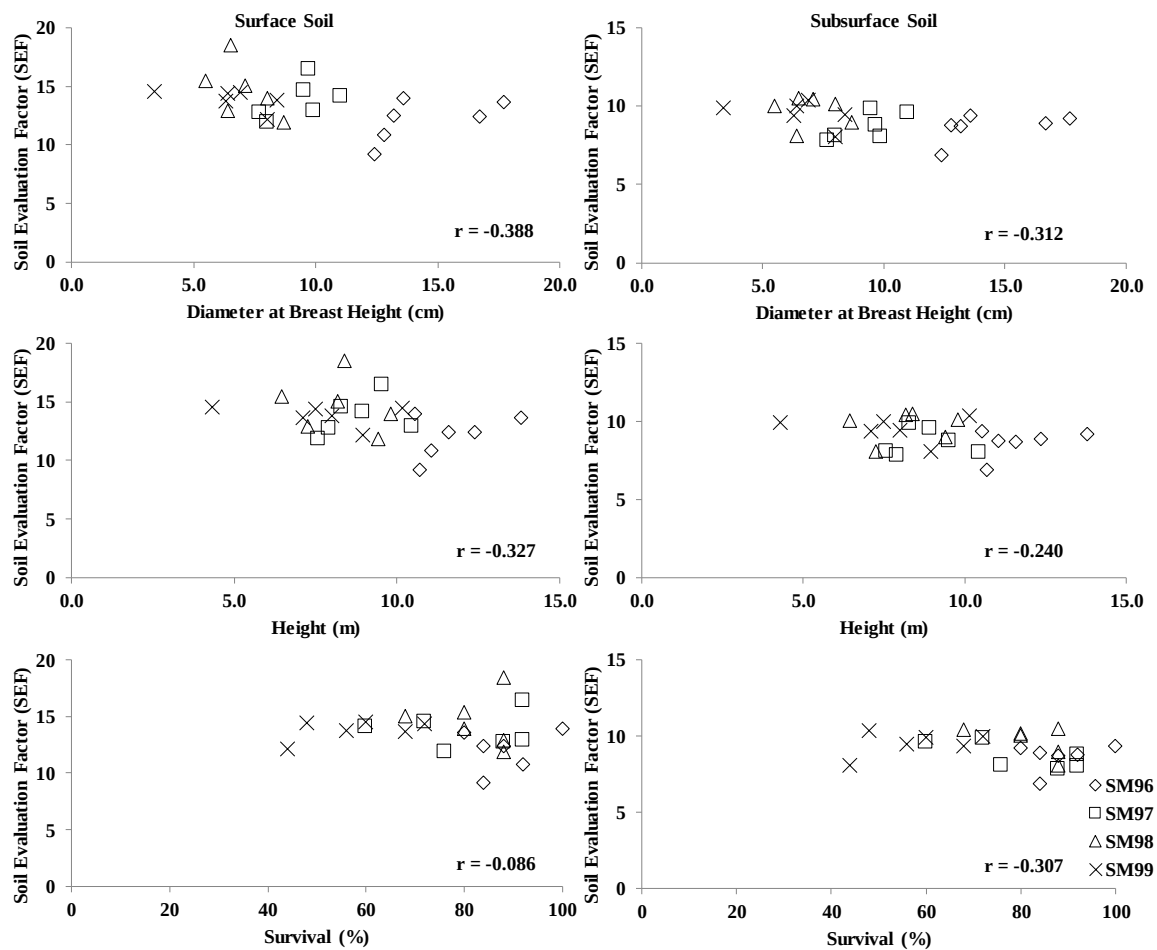


Figure 6.5: Relationship between diameter at breast height (DBH), height, and percentage of survival with Soil Evaluation Factor (SEF) derived from surface and subsurface soils.

Table 6.5: Summary of the relationship between PC1 score, SFI, SEF, and tree growth parameters (diameter at breast height (DBH), height, and percentage of survival).

Growth Parameters	PC1		SFI		SEF	
	Surface (0-10 cm)	Subsurface (30-40 cm)	Surface (0-10 cm)	Subsurface (30-40 cm)	Surface (0-10 cm)	Subsurface (30-40 cm)
DBH	0.546**	0.437*	0.565**	-0.043	-0.388	-0.312
Height	0.352	0.296	0.483*	-0.053	-0.327	-0.240
Survival	0.477*	0.183	0.684**	-0.014	-0.086	-0.307

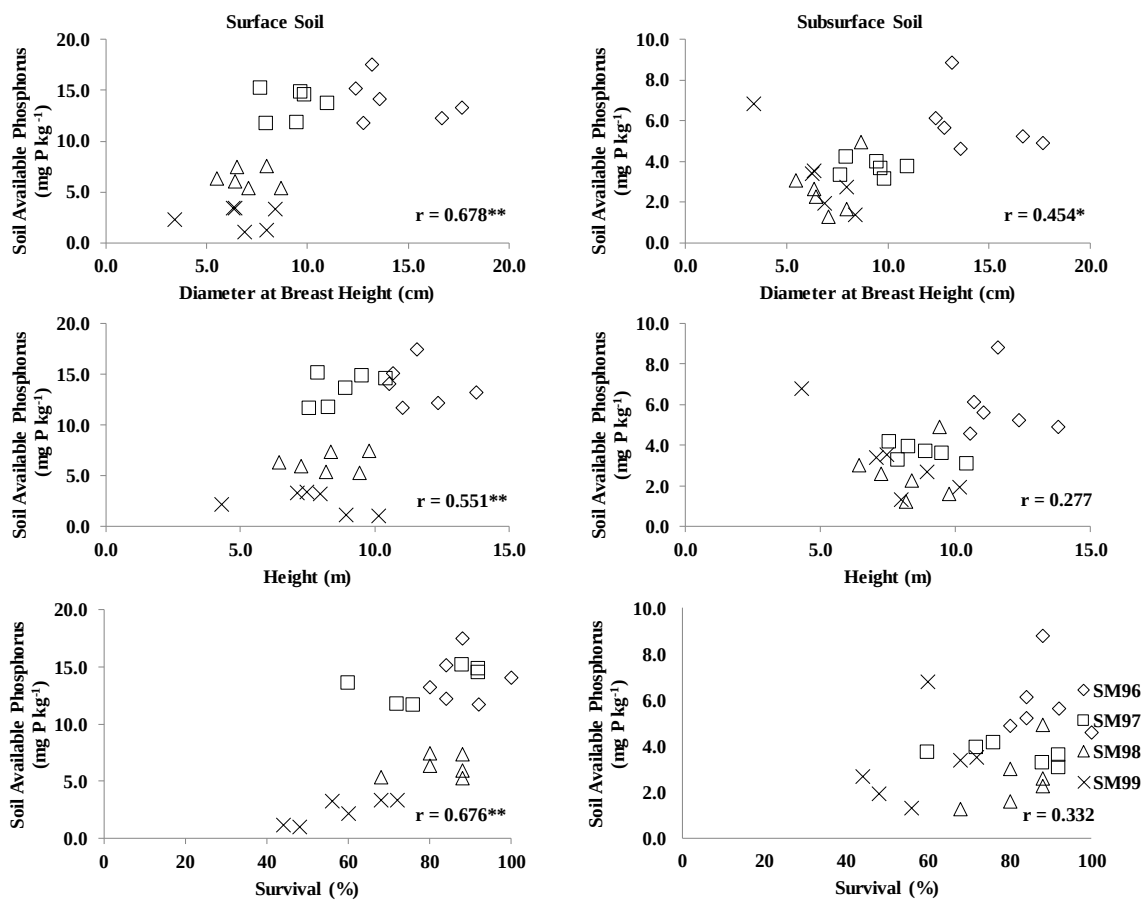


Figure 6.6: Relationship between soil available phosphorus with diameter at breast height (DBH), height, and percentage of survival derived from surface and subsurface soils. *, ** Correlations are significant at 5% and 1% levels, respectively, using Pearson correlation matrix.

A positive correlation was also observed between soil available phosphorus and the height and survival percentage at surface soils ($r = 0.551^{**}$ and $r = 0.676^{**}$, $P < 0.01$, respectively). Based on Figure 6.6, the soil available phosphorus is directly proportional to the diameter at breast height, tree height, and survival percentage of the planted *S. macrophylla* in the rehabilitation sites. Consequently, based on the results of correlation at surface soils, it can be deduced that soil available phosphorus (DBH: $r = 0.678^{**}$, $P < 0.01$; height: $r = 0.551^{**}$, $P < 0.01$) is clearly a better indicator of *S. macrophylla* productivity than the SFI (DBH: $r = 0.565^{**}$, $P < 0.01$; and height: $r = 0.483^{*}$, $P < 0.05$) in the present study. According to our previous study (Perumal et al., 2015, 2017a), an increase in the growth and survival percentage of *S. macrophylla* in SM96 and SM97 was related to the high content of available phosphorus in soils whereas the low content of available phosphorus was related to a decrease in the growth and survival percentage of the planted trees in the SM98 and SM99 sites. One possible reason for the poor growth rate of the planted *S. macrophylla* especially in study sites SM98 and SM99 was due to the low availability of soil phosphorus pools in the form of organic and inorganic phosphorus in the bulk soil, which would limit the uptake of plants. Phosphorus is transported principally by diffusion, whereas soluble minerals such as potassium, K, are transferred via the soil through bulk flow and diffusion. High plant uptake rates create a zone around the root which is depleted of P since the rate of P diffusion is slow (Schachtman, et al., 1998). According to Perrott et al. (1990) and Frossard et al. (2000), the content of soil available P largely depends on a combination of factors including the uptake of plant, adsorption-desorption, and dissolution-precipitation of inorganic P, organic P mineralisation, microbial immobilisation, and addition of fertiliser. Immobile forms of P to the soil solution were released by soil microbes and the microbes are responsible for the P immobilisation (Schachtman et al., 1998). Likewise, a study conducted

in unimproved grassland and 19-year-old stand by Chen et al. (2003) concluded that the recycling of P was largely driven by plant P demand and sustained by leaf litter inputs and root in forest ecosystems. Environmental factors such as the amount of rainfall, soil temperature, and moisture might also influence the availability of P.

CHAPTER 7

**INFLUENCES OF INORGANIC AND ORGANIC FERTILISERS TO
MORPHOLOGICAL QUALITY ATTRIBUTES OF *Shorea macrophylla* (DE
VRIESE) P.S. ASHTON SEEDLINGS IN A TROPICAL NURSERY**

7.1 Introduction

In the humid tropics of Borneo, *Shorea macrophylla* is one of the common indigenous tree species mainly chosen for tropical forest rehabilitation and reforestation programs on the basis of its socio-economic and ecological importance in Sarawak, Malaysia (Perumal et al., 2015, 2017a, 2017b, 2019). This endemic riparian species, locally known as “*Engkabang jantong*” (Light Red *Meranti*) (in Malaysia) and “*Tengkawang Hantelok*” (in Indonesia) belongs to the family of Dipterocarpaceae, the most important family of tropical rainforest trees in Southeast Asia (Utomo et al., 2018). *S. macrophylla* is a medium to a large timber-sized tree and the seeds are highly valued for its oil-bearing fruits or known as the large-fruited species of illipe nuts, a substitute for cocoa butter, and sources of a fatty substance that can be used as medicine (Connell, 1968; Tompsett & Kemp, 1996; Ng et al., 2002). Under the natural condition in suitable areas, this canopy species can attain a height of 50 m, 50-60 cm in diameter at breast height within 20-23 years (Newman et al., 1996) and 2.0 m in buttress height in the Mixed Dipterocarp Forests of Sarawak and Brunei (Ashton, 1964, 1982). This lowland tree species is one of the fastest growing species in the genus (*Shorea*), and is found frequently in wet habitats, such as along the rivers and in areas which are periodically inundated (Ashton, 1998; Perumal et al., 2017a, 2017b; Mohamad Jaffar et al., 2018a, 2018b, 2018c; Perumal et al., 2019). *S. macrophylla* flowers sporadically in mass flowering years (Appanah & Weinland, 1993) and produces recalcitrant seeds with at most

1-month viability after collection (Ng, 1976). Due to their fast growth and hardiness to endure harsh or disturbed conditions, *S. macrophylla* is a prime candidate for reforestation programs in the humid tropics with poor soils.

Experimental reforestation programs using nursery-produced seedlings can be an effective means of ensuring successful establishment and rapid growth following outplanting (Pinto et al., 2011). According to Scagel et al. (1998), the success of reforestation regularly depends on considerations and decisions made prior to planting, such as seedling morphology, seedling stocktype, genetics, site preparation, site limiting factors, planting techniques, and the outplanting window. However, several constraints on dipterocarp seedling production due to irregular flowering and unpredictable fruiting intervals in the tropics had restricted the scale of reforestation programs (Tang & Tamari, 1973; Chan & Appanah, 1980; Lo, 1985; Aminah et al., 1995). In particular, more than 70% of emergent trees of the family Dipterocarpaceae, which dominates the tropical rain forests of South East Asia are involved in mass flowering events, but seldom reproduce in other years (Sakai et al., 1999; Ichie & Nakagawa, 2013). In Southeast Asia, reforestation using dipterocarps has been initiated by several researchers (Ådjers et al., 1995, 1996; Sakurai et al., 1999; Arifin et al., 2008; Wasli et al., 2014; Perumal et al., 2015, 2016, 2017a, 2017b).

Seedling quality is generally defined as “fitness for purpose” (Mattsson, 1997), which indicates that quality seedlings should meet the desired level of survival and growth upon outplanting. Despite advances in seedling quality testing and the prediction of field performance, no single characteristic or test has been proved suitable across a wide range of species and conditions (Dey & Parker 1997; Jaenicke, 1999; Davis & Jacobs, 2005). This suggests that superior seedling attributes that associate with survival and growth in the field need to be investigated and determined for any species intended for planting. Various

seedling quality assessment methods and their importance in forecasting field performance have been developed and tested over the past two decades (Folk & Grossnickle, 1997; Mattsson, 1997; Mohammed, 1997; Grossnickle & MacDonald, 2018). Seedling morphological attributes are the most common attributes used in seedling quality assessment since they are cheap and easy to be measured (Mexal & Landis, 1990), however this is rarely done in Malaysia. Unlike physiological attributes, they do not require sophisticated equipment and advanced training to evaluate them (Nyoka et al., 2018). Seedling morphological attributes, such as shoot height, root collar diameter, sturdiness, root biomass, shoot biomass (Haase, 2008), and root to shoot ratio are widely used to assess seedling quality in nursery and at the time of planting.

Proper application of fertiliser based on different types is important for nursery productivity and seedling quality. Fertilisation is one of the essential cultural practices for seedling quality in reforestation as it can accelerate the growth of the shoots and roots of seedlings (Chun et al., 2012). Though, poor response of the dipterocarp seedlings to easily soluble or liquid fertiliser has been suggested (Turner et al., 1993; Lee & Alexander, 1994). Fertilisation affects root and shoot growth of plants, improves post-transplant rooting and growth capacity, and increases resistance to water stress, low temperature and disease (van den Driessche, 1991, 1992; Malik & Timmer, 1998; Shaw et al., 1998; Grossnickle, 2000; Fløistad & Kohmann, 2004). These characteristics are of crucial importance for successful early establishment under unfavourable conditions (Puttonen, 1997), and can be influenced substantially by alternative fertilisation regimes.

Many studies have documented the influences of fertilisation or mineral nutrition on seedling quality for reforestation, though most of these focus on conifers from wet, temperate forests, with emphasis on nitrogen additions (Green & Mitchell, 1992; Green et al., 1994;

Timmer & Aidelbaum, 1996; Folk & Grossnickle, 1997; Tan & Hogan, 1997; Irwin et al., 1998; Quoreshi & Timmer, 2000; Jose et al., 2003). Relatively very little is known and no clear consensus exists, whether seedling production based on different types of fertilisation regimes influence initial seedling morphological quality attributes on the capacity of dipterocarp species from Malaysia to resist transplanting stress once outplanted. Although considerable studies on seedling quality have been carried out in temperate regions (Europe and North America) and in other tropical and subtropical regions in Australia and Asia, many of these studies have focused on seedlings for commercial plantations with very little work on seedlings destined for restoration and agroforestation (Nyoka et al., 2018). Nonetheless, previous studies also reported that simple fertigation did not improve the growth of pot grown dipterocarp seedlings in the nursery (Turner et al., 1993; Lee & Alexander 1994). Thus, the effective methods of fertiliser application under nursery and field conditions have not been thoroughly developed and quantified.

The objective of the present study was to determine the influences of inorganic and organic fertilisers on the seedling morphological quality attributes of *S. macrophylla* in a tropical nursery as to produce healthy and quality seedlings in ensuring better field performance. The assessment focused on the influences of different types of fertilisers on the morphological attributes, which collectively provide adequate information on the quality of seedlings as well as their likelihood of survival and growth upon outplanting. The results of the present study could provide some useful applied information as well as guidelines to the nursery community and forest managers towards improving the current nursery management practices and physical seedling quality assessment which may enhance seedling survival and productivity for future successful reforestation programs in Sarawak, Malaysia. We, specifically, addressed the following question in this study: To what extent

do different types of fertilisers affect seedling performance of *S. macrophylla* at the end of nursery culture prior to outplanting?

7.2 Materials and Methods

7.2.1 Study Site

This study was conducted in the Universiti Malaysia Sarawak (UNIMAS) Forest Research Nursery located in Kota Samarahan, Sarawak, Malaysia and detail information on the location and climatic data was mentioned in Chapter 3.

7.2.2 Seed Collection and Seedling Production

Seeds of *S. macrophylla* were collected from Sampadi Forest Reserve, Lundu, Sarawak (N01°34'13", E109°53'12") during a masting event, which began in late January-February 2015. On February 7, 2015, visibly healthy (i.e., free of fungus, decay, and herbivore damage) and uniform sized seeds were selected, dewinged, and sown directly into black, perforated, polyethylene bags (15.2 cm in diameter, 22.9 cm in deep) with several drainage holes at the bottom. Bags were placed bare ground under a white transparent net. To maintain optimum soil moisture, seedlings were watered once a day at the beginning and then as required. Hand weeding was done regularly.

7.2.3 Preparation of Growing Medium and Fertilisation Treatments

The controlled-instant release fertiliser (CIRF) treatment used in this study was a blend of 80% polyurethane coated controlled-release fertiliser (CRF) with 20% uncoated instant release fertiliser. The CRF was designed by the manufacturer which consists of prills that expected to display an 80% elution of its nutrients within 360 days assuming a soil

temperature of 25°C at position of fertiliser placement. The uncoated fertiliser disperses its nutrients instantly under normal watering condition (once daily). For seedling production in the nursery, the pots were filled with about 2.0 kg of 1:1 mixture of topsoil and sand (v:v), following the standard forest nursery practice for dipterocarp species adapted in Sarawak. The initial and final (270 Days After Sowing) chemical characteristics of the growing medium are presented in Table 7.1. The three fertiliser formulations, either a chemical fertiliser (CF, N: P: K = 10: 26: 10) (control) or a controlled-instant release chemical fertiliser (CIRF, N: P: K = 10: 26: 10), SK CoteTM Plus or an organic jellyfish fertiliser (JF, N: P: K = 13.1: 1.7: 0.03), Marutomo Corporation, Japan was applied at the rate of 5 g per pot. The CF, CIRF, and JF fertiliser was applied as a top dressing of the polyethylene bags. These application rates corresponded to 0.855 kg ha⁻¹ at a density of 171 seedlings ha⁻¹ for CF, CIRF, and JF treatments. The rationale or criteria for selecting these three types of fertilisers in this study was to compare the effectiveness of chemical and organic fertilisers in relation to the morphological development of *S. macrophylla* seedlings at nursery stage. Since this was the first attempt of the study for testing *S. macrophylla* seedlings, the usage of controlled-instant release and organic jellyfish fertilisers as the alternative approach of conventional straight chemical fertiliser by Forest Department of Sarawak for producing seedlings in the nursery for reforestation programs was applied.

Table 7.1: Initial and final (270 DAS) chemical characteristics of the growing medium.

Soil Chemical Parameters		Soil Chemical Properties			
		Initial	Final (270 DAS)		
			CF	CIRF	JF
pH (H ₂ O)		5.30 ± 0.12	5.58 ± 0.26	4.79 ± 0.25	5.23 ± 0.28
EC ^a	(µS cm ⁻¹)	28.2 ± 1.2	40.1 ± 8.2	52.8 ± 18.6	17.3 ± 8.8
Total C ^b	(g kg ⁻¹)	26.0 ± 1.8	17.6 ± 2.5	16.5 ± 1.9	10.1 ± 3.3
Total N ^c	(g kg ⁻¹)	0.63 ± 0.19	0.33 ± 0.11	0.19 ± 0.07	0.18 ± 0.06
Available P	(mg P kg ⁻¹)	1.30 ± 0.09	73.5 ± 29.2	128.3 ± 70.8	1.4 ± 0.4
Exch. K ⁺	(cmol _c kg ⁻¹)	16.3 ± 2.6	0.09 ± 0.08	0.14 ± 0.04	0.03 ± 0.03

Values in the same column indicate means ± standard deviation, ^a EC: Electrical Conductivity, ^b Total C: Total Carbon; ^c Total N: Total Nitrogen.

7.2.4 Methods for Subsequent Seedling Survival Rate and Growth Assessment

A sample of 57 seedlings from each fertiliser treatment were selected for seedling survival rate and subsequent growth assessment. Seedling survival rate, shoot height, root collar diameter, and number of leaves were recorded and monitored every 30 days commencing 45 Days After Sowing (DAS) until the end of the nursery growing season (270 DAS). Relative growth rate (RGR) for shoot height and root collar diameter was calculated using the following equation (Kramer & Kozlowski 1979):

$$\text{RGR} = \left(\frac{\ln X_2 - \ln X_1}{\Delta t} \right)$$

where X_1 and X_2 denote variables measured at the time of the first and second assessments, respectively and Δt is the time interval between the two measurements. Seedling total leaf surface area estimation was adapted following the method of Blanco and Folegatti (2003). At 90 DAS, a total of five leaves were collected from each of 12 seedlings per fertiliser treatment and measurements of the leaf length and leaf width were taken. The actual surface

area of each leaf was measured using a portable LI-COR leaf surface area meter conveyor. A mathematical model was obtained by correlating the parameters of leaf length (L), width (W), length x width (LW), length + width (L+W), length x length (L²) or width x width (W²) to the actual leaf area (LA) of the total 60 leaves sample using regression analysis. The regression equation with the highest R^2 values was selected to construct the mathematical formula for leaf surface area estimation in each of the treatment. Thus, the fitted regression equations for leaf surface area estimation of seedlings were as follows: -

Chemical Fertiliser (CF) treatment:

$$LA_{\text{est}} = -20.9 + 4.68 W + 0.664 (LW), \text{ where } R^2 = 0.98, n = 60$$

Controlled-Instant Release Fertiliser (CIRF) treatment:

$$LA_{\text{est}} = 2.4 + 0.960 (LW) - 0.102 L^2, \text{ where } R^2 = 0.95, n = 60$$

Jellyfish Fertiliser (JF) treatment:

$$LA_{\text{est}} = -199 + 14.9 (L + W) - 0.215 L^2, \text{ where } R^2 = 0.96, n = 60$$

where, LA_{est} = estimated leaf area (cm²)

W = width of leaf (cm)

LW = product of leaf length and leaf width (cm²)

L+W = sum of leaf length and leaf width (cm)

L² = square product of leaf length (cm²)

Therefore, in order to estimate the total leaf surface area of seedlings, 15 seedlings from the total of 57 seedlings of growth assessment in each treatment was randomly selected for detailed measurements of leaf length and leaf width at an interval of every 30 days until the end of the nursery growing season (270 DAS). The leaf length and leaf width measurements were then inserted into the mathematical formula of each treatment as to estimate the leaf surface area of *S. macrophylla* seedlings.

7.2.5 Methods for Seedling Biomass Production

Following the final measurements at the end of the nursery growing season (270 DAS), 12 seedlings from the total of 57 seedlings in each treatment was randomly selected and harvested using destructive sampling techniques for seedling biomass production. Each seedling was tagged and then washed with tap water carefully to remove any remaining growing medium and other debris. Each plant part including the leaves, stems, and roots were partitioned and the measurement of biomass was performed. All the plant parts were oven dried to a constant weight at 60°C for five days (120 hours) and their biomass were recorded. Total biomass was obtained by adding dry weights of leaves, stems, and roots.

7.2.6 Experimental Design and Statistical Analysis

The three fertiliser treatments (CF, CIRF, and JF) were randomly assigned to each seedling and arranged in a completely randomised design (CRD). A total of 57 seedlings per fertiliser treatment were used for subsequent seedling survival and growth assessment in the experiment. Treatments and replications were rearranged monthly and placed on bare ground of the nursery to ensure that the seedlings were subjected to a similar growing environment. In order to compare and determine whether survival rate and morphological quality attributes

of seedlings under nursery conditions were significantly affected among different types of fertiliser treatments, a one-way Analysis of Variance (ANOVA) for a completely randomised design was performed at the end of the nursery growing season (270 DAS). Tukey's Honestly Significant Difference (HSD) test was chosen as post-hoc test to compare mean values of the treatments at 5% significance level ($P < 0.05$). All the statistical analyses were performed using Statistical Software Package for the Social Sciences (IBM, Version 24.0 for Windows) (SPSS Inc., 2016) and the results are reported as mean $\pm$ standard deviation.

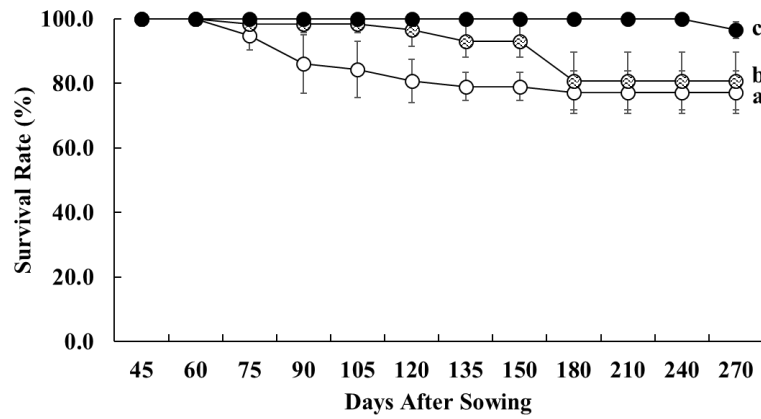
7.3 Results and Discussion

7.3.1 Effects of Inorganic and Organic Fertilisers on Subsequent Seedling Survival Rate and Morphological Quality Attributes at the End of Nursery Growing Season

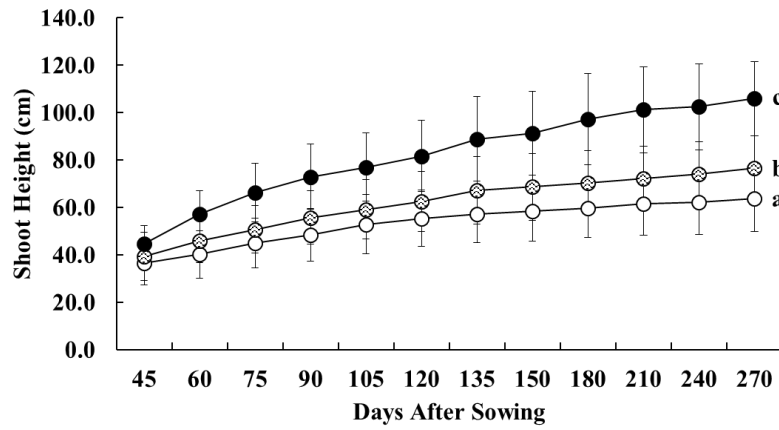
The cumulative seed germination percentage of *S. macrophylla* among different types of fertilisations were similar (CF: 97.4%, CIRF: 98.0%, JF: 95.3%) and this indicated that uniform seeds were used for the experiment. One-way analysis of variance showed that mean survival rate of *S. macrophylla* seedlings was significantly influenced ($P < 0.05$) by fertiliser regimes at the end of nursery culture (270 DAS) as shown in Figure 7.1a. Fertilisation apparently had a significant effect on mean seedling survival although survival was $> 75\%$ throughout the experiment in all treatments. At 270 DAS, JF treatment depicted the highest mean survival rate followed by CIRF and CF treatments with 96.5%, 80.7%, and 77.2%, respectively.

Figures 7.1b and 7.1c show the mean shoot height and root collar diameter growth trends among different fertiliser treatments. The effects of fertiliser regimes on

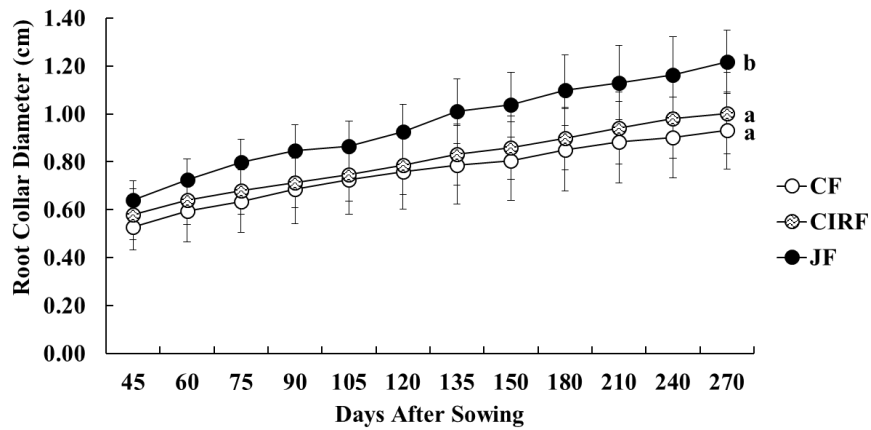
morphological quality attributes of *S. macrophylla* seedlings at the end of nursery growing season were variable among different treatments. The fertiliser treatments had significant effects ($P < 0.05$) on all the seedling morphological quality attributes except for root to shoot ratio (Table 7.2). Morphologically, all the seedling quality attributes were significantly higher for jellyfish fertiliser treatment as compared to controlled-instant release and chemical fertiliser treatments. However, there were no significant differences ($P > 0.05$) detected between the inorganic fertilisers (CF and CIRF treatments) for root collar diameter, relative growth rate of root collar diameter, number of leaves, total leaf surface area, shoot biomass, root biomass, and total biomass. The selected root and shoot development of *S. macrophylla* seedlings at the end of nursery growing season (270 DAS) for all the fertiliser treatments were shown in Figure 7.2. Based on Table 7.2, although there were no significant differences ($P > 0.05$) obtained among different fertiliser treatments at the end of nursery culture for mean root to shoot ratio, the seedlings of *S. macrophylla* in all the treatments were fit to the general expectations of a balanced root to shoot ratio. Likewise, the mean sturdiness quotients presented in Table 7.2 does not meet the ideal expectations among all the fertiliser treatments throughout the experiment, which postulates greater values than 6 (Gregorio et al., 2004).



(a)



(b)



(c)

Figure 7.1: Effects of inorganic and organic fertilisers on mean survival rate and growth trends of *S. macrophylla* seedlings at the end of nursery growing season (270 DAS). (a) survival rate. (b) shoot height. (c) root collar diameter. Different letter(s) indicate significant differences among treatments at $P < 0.05$ using Tukey's HSD test for 270 DAS.

Table 7.2: Effects of inorganic and organic fertilisers on the seedling morphological quality attributes of *S. macrophylla* at the end of nursery growing season (270 DAS).

Treatments/ Morphological Quality Attributes		Chemical Fertiliser (CF)	Controlled-Instant Release Fertiliser (CIRF)	Jellyfish Fertiliser (JF)
Shoot Height	(cm)	63.8 ± 13.7 a	76.8 ± 13.5 b	105.9 ± 15.6 c
Root Collar Diameter	(cm)	0.93 ± 0.16 a	1.00 ± 0.17 a	1.22 ± 0.13 b
Sturdiness Quotient		6.91 ± 1.29 a	7.74 ± 1.22 b	8.78 ± 1.55 c
RGR _{sh}	(cm cm ⁻¹ day ⁻¹)	0.110 ± 0.054 a	0.167 ± 0.061 b	0.272 ± 0.065 c
RGR _{cd}	(cm cm ⁻¹ day ⁻¹)	0.0017 ± 0.0007 a	0.0019 ± 0.0008 a	0.0025 ± 0.0005 b
Number of Leaves		7 ± 3 a	7 ± 3 a	11 ± 4 b
Total Leaf Surface Area	(cm ² seedling ⁻¹)	1106.5 ± 374.1 a	1038.7 ± 378.2 a	2353.7 ± 455.5 b
Shoot Biomass	(g)	17.1 ± 7.1 a	16.2 ± 9.3 a	32.9 ± 11.6 b
Root Biomass	(g)	14.1 ± 7.1 a	12.9 ± 6.3 a	31.0 ± 20.2 b
Total Biomass	(g)	31.2 ± 13.6 a	29.2 ± 15.0 a	63.9 ± 30.0 b
Root to Shoot Ratio		0.81 ± 0.29 ns	0.83 ± 0.19 ns	0.92 ± 0.38 ns

Means ± standard deviation values in the same row followed by different letter(s) indicate significant differences among treatments at $P < 0.05$ using Tukey's HSD test; ns: no significant differences; RGR_{sh}: Relative Growth Rate of Shoot Height; RGR_{cd}: Relative Growth Rate of Root Collar Diameter.



Figure 7.2: Selected root and shoot development of *S. macrophylla* seedlings at the end of nursery growing season (270 DAS). (a) chemical fertiliser treatment (CF); (b) controlled-instant release fertiliser treatment (CIRF); (c) jellyfish fertiliser treatment (JF).

The mortality of *S. macrophylla* seedlings in the CF treatments was approximately 14% within 90 days after fertilisation due to foliar and root necrosis. This mortality was possibly due to the higher salinity induced by CF, due to its fast release of nutrients which could have slightly worsened the root conditions. A similar trend was reported by Irino et al. (2004) where 40% of the *Dryobalanops lanceolata* seedlings died within 30 days after treated with chemical fertiliser due to foliar and root necrosis. Previous study concluded that dipterocarp seedlings were less responsive to easily soluble or liquid fertilisers since most of the dipterocarp species are characterised by a relatively slow growth (Turner et al., 1993, Lee & Alexander, 1994). In the present study, the CIRF and JF treatments promoted higher seedling survival at (75 to 270 DAS) as compared to CF treatment.

In our study, seedling morphological quality attributes were found to be significantly higher when treated with jellyfish fertiliser as compared to those treated with chemical fertiliser and controlled-instant release fertiliser. Findings from this study revealed that the application of jellyfish fertilisation had enhanced and yielded better seedling growth performance of *S. macrophylla*, i.e. they have a beneficial influence on the improvement of growth parameters of seedlings as compared to chemical fertilisations.

The findings indicated that seedlings of *S. macrophylla* raised in the nursery were of sub-optimal quality since the sturdiness quotient values exceeded 6. A sturdiness quotient of less than 6 has been recommended as a desired characteristic of high-quality seedlings in tropical systems (Jaenicke, 1999). Previous studies by several researchers have also found sturdiness quotient to correlate with seedling survival rate and initial growth following outplanting (Mexal & Landis, 1990; Ivetić et al., 2017). According to Takoutsing et al. (2014), seedlings with sturdiness ratio greater than six were basically tall and thin (lanky)

and etiolated, whereas a small quotient indicates sturdy plants with a higher chance of survival, particularly on windy or dry sites.

Nonetheless, seedlings from CF, CIRF, and JF treatments were found to have a root to shoot ratio values within the acceptable range ($RS < 2$) and generally these seedlings are likely to withstand the adverse conditions in most planting sites due to the adequate root system that will not impede the growth of the plant. Root to shoot ratio of ≤ 2 have been suggested by Jaenicke (1999), Haase (2007), and Nyoka et al. (2018) as the desired threshold characteristic of the high and good quality of container seedlings. According to Haase (2007), the ratio measures the balance between the transpirational area (shoot) and the water absorbing area (root) of the seedlings. This ratio is premised on the fact that well-developed roots are important to the seedlings to absorb sufficient amount of water and nutrients, while shoots provide for a pathway through which water and nutrients absorbed by roots are pumped to the leaves for photosynthesis purposes and cooling the plant through transpiration (Nyoka et al., 2018). In addition, the findings also substantiate those of Gregorio et al. (2005) who found that seedlings with a low root to shoot ratio have a greater survival rate than the seedlings with higher root to shoot ratios. Several factors which influenced the root to shoot ratio are cultural practices (Johnson & Cline 1991; Ericsson, 1995), genetics, seedlings age, container size, and the species.

Since the present study was the first to examine the influences of CF, CIRF, and JF fertilisers on the morphological quality attributes of *S. macrophylla* seedlings as to produce healthy and quality seedlings in ensuring better field performance, our results clearly showed that all types of fertilisers (CF, CIRF, and JF) are beneficial in raising the seedlings. It can be considered that less nutrient requirement is essential when raising the seedlings at nursery stage since all of these seedlings are produced under controlled environment which resulted

in less nutrient requirement for *S. macrophylla* seedlings developmental growth. Based on the root development of seedlings as shown in Figure 7.2, *S. macrophylla* seedlings in CF and CIRF treatments could be raised over a much longer period (even after more than 9 months as stock in the nursery) until the initiation of transplantation in rehabilitation programs. However, for seedlings in JF treatment, it should be outplanted at 270 DAS (9 months) at the field as to avoid root deformations in the polyethylene bags. However, based on the findings in this study, poor seedling quality attributes will be expected on *S. macrophylla* seedlings if all the treatments were kept in the nursery beyond 270 DAS. According to Takoutsing et al. (2014), root deformations sometimes are attributed to the duration of the seedlings and the type of substrate used in the nurseries. Previous study by Irino et al. (2004) suggested that dipterocarp seedlings could be raised to 16 months, as observed in their experiment. The use of controlled-release fertiliser (CRF) had enable to maintain the raised *Dryobalanops lanceolata* seedlings under good conditions even after more than 1 year as stock in the nursery (Irino et al., 2004).

Several researchers emphasised that the production of seedlings with a large, vigorous root system and a root to shoot ratio to match the needs of the outplanting site is a significant factor in the successful seedling establishment (McDonald, 1991; Barnett & McGilvray, 1993; South et al., 2005b). Edwards (1998) added that seedlings with large root systems are better able to withstand outplanting shock and usually grow well in the year following outplanting as compared to seedlings with high root to shoot ratios. Likewise, a study by Nyoka et al. (2018) in Malawi reported that seedlings with small root systems in relation to shoot were not able to adequately supply sufficient water to shoots during the long dry season.

In this study, *S. macrophylla* seedlings treated with jellyfish fertiliser showed better and favourable growth performance at the end of nursery growing season (270 DAS). This was presumably due to the absorption of water and nutrients from the soils in the growing medium to the fertiliser and return carbon and nutrient contents to a balance and more favourable state which is readily available for the uptake of seedlings (Caravaca et al., 2002). In addition, jellyfish can be used as a source of organic fertiliser for enhancing tree growth as well as for improving soil properties in terms of physical and chemical properties. Theoretically, jellyfish fertiliser comprises of high organic matter (approximately 81%), which plays an essential role in improving the physical structure of the soil; and consequently, increases the soil moisture. It creates a vapour barrier between the soil and the atmosphere, resulting in a decrement in soil temperature and evaporative water loss when jellyfish fertiliser is distributed over the soil surface (Power, 2002). Likewise, Nyoka et al. (2018) pointed out that amendments using organic matter can help in maintaining or improving soil properties including soil bulk density, soil structure, water and nutrient holding capacity, and the environment for the growth of beneficial rhizosphere microorganisms. Nevertheless, the improvement in soil aggregation by organic matter addition positively affects the seeds germination as well as the growth and development of shoots and roots (Noordwijk et al., 1993).

CHAPTER 8

EFFECTS OF INITIAL SEEDLING AGE ON THE OUTPLANTING PERFORMANCE: THE CASE OF MALAYSIAN BORNEO TROPICAL INDIGENOUS SPECIES, *Shorea macrophylla* (DE VRIESE) P.S. ASHTON

8.1 Introduction

Seedling quality is a critical component in establishing successful forest restoration programs (Grossnickle & MacDonald, 2018). Choosing suitable tree species and provenance, applying proper nursery cultural practices to produce quality seedlings, ensuring proper seedling handling practices, and making site modifications to improve the physical environment of the restoration site are among the pivotal steps in ensuring initial success of forest establishment (Grossnickle, 2000). Seedling quality is generally defined as “fitness for purpose”, with the focus on identifying and discarding seedlings that are not likely to survive or will not grow very well following outplanting (Mattsson, 1997). The morphological criteria for seedling quality assessment can be manipulated by nursery cultural practices (Akpo et al., 2014). The effect of nursery management practices on seedling quality attributes has been studied on numerous range of plant species at nursery and field including dipterocarp (*Dryobalanops lanceolata*) (Irino et al., 2004, 2005), *Eucalyptus* (Close et al., 2010), date palm (*Phoenix dactylifera* L.) (Aisueni et al., 2009), pine (*Pinus palustris* Mill.) (South et al., 2005b) Spanish fir (*Abies pinsapo* Boiss.) (Navarro et al., 2006), *Acacia koa* (Dumroese et al., 2011), oil palm (*Elaeis guineensis* Jacq.) (Akpo et al., 2014), western larch (*Larix occidentalis* Nutt.) (Aghai et al., 2014), and white jabon (*Anthocephalus cadamba* [Roxb.] Miq.) (Budiman et al., 2015).

Various previous studies showed that age and size are two reliable, easy-to-use indicators of seedling quality (Close et al., 2010). According to Li et al. (2011), larger seedlings can be produced by prolonging the culturing period of seedlings in the nursery, i.e., increase the age of seedlings at the time of planting. Larger seedlings usually have better performance than smaller seedlings after planting (South et al., 2005a; Cuesta et al., 2010), particularly under conditions of competition for resources with weeds (South & Mitchell, 1999) and vertebrate herbivore browsing (Close et al., 2010), while decreasing survivals with increasing seedling sizes were detected on extremely harsh sites (Puértolas et al., 2012). Grossnickle (2000) specified that larger stock with greater foliar mass allowed for increased photosynthetic capacity, which facilitated rapid growth and fast utilisation of site resources during establishment. Nonetheless, the larger stock has higher carbohydrate storage and nutrient which can promote outplanting performance (Oliet et al., 2009).

In addition, research undertaken in New Zealand, Scotland, South Africa, and the United States advocate the use of large-diameter stock, which performs consistently better than small-diameter stock regardless of silvicultural methods used (South et al., 1993b). However, these findings are not true for all species, site conditions, and site preparation methods since the post-planting performance of large stock of a given species are likely dependent on the reforestation site conditions (Li et al., 2011). The actual performance of newly planted seedlings depends not only on the inherent performance potential (seedling quality) of seedlings but also to what extent the site environmental conditions allow this potential to be expressed (Folk & Grossnickle, 1997).

However, the success of nurseries in producing high-quality seedlings have not been fully investigated and information about the performances of the seedlings after leaving the nurseries for outplanting is required (Degrande et al., 2012). Most of these previous studies

focus on conifers from wet, temperate forests, with emphasis on nitrogen additions (Jose et al., 2003). Relatively very little is known and no clear consensus exists regarding the factors influencing the relationship between initial seedling age with outplanting performance on the capacity of tropical indigenous dipterocarp species from other ecoregions, particularly Malaysia to resist post-planting stress. Several constraints on dipterocarp seedling production due to irregular flowering and unpredictable fruiting intervals in the tropics had restricted the scale of reforestation programs (Aminah, 1995). In particular, more than 70% of emergent trees of the family Dipterocarpaceae, which dominates the tropical rain forests of South East Asia are involved in mass flowering events but seldom reproduce in other years (Sakai et al., 1999; Ichie & Nakagawa, 2013). Even though considerable research on seedling quality has been conducted in temperate regions (North America and Europe) and in some other tropical and subtropical regions in Asia and Australia, most of these studies have highlighted on tree seedlings for the purpose of commercial plantations with very little work on seedlings destined for restoration and agroforestation (Nyoka et al., 2018).

Over the past two decades, various seedling quality evaluation approaches and their importance in subsequent outplanting performance have been developed and tested (Grossnickle & Mac Donald, 2018). Unfortunately, there are conflicting recommendations as to which nursery practices and attributes are best due to the great variation in seedling quality (Stone et al., 2003) and field performance (South et al., 2001). Commonly measured main seedling morphological quality attributes to address stock quality at the time of planting include shoot height, root collar diameter, shoot biomass (Haase, 2008), root biomass, and root to shoot ratio. These attributes are fairly simple to measure in operational settings and exhibit a good correlation with outplanting performance in many cases (Jacobs et al., 2005).

Despite advances in seedling quality trials and outplanting performance, no single attribute has proved suitable across a multitude of species and conditions (Davis & Jacobs, 2005).

Since the research on seedling quality testing and field performance has received meagre attention in Malaysia, the relationship between containerised seedling size and subsequent survival and growth in the field needs to be determined. This study was undertaken to investigate the effects of initial seedling age on the subsequent outplanting performance of *Shorea macrophylla*. It is hoped that their socio-economic and ecological importance in the region will motivate nursery practitioners and forest managers to undertake enrichment planting in State forest reserves which, in turn, justify the study on seedling quality assessment. Notwithstanding, such seedling quality information could be used within the “target plant concept” to enable nursery practitioners, foresters, and land managers to have an effective dialogue on how seedlings with morphological attributes will meet forest restoration objectives. Although planting seedlings with desirable plant attributes does not guarantee high survival and good growth after outplanting, planting seedlings with desirable attributes could increase chances for a future successful forest restoration program in Sarawak, Malaysia. We, specifically, addressed the following questions in this study: (1) To what extent do seedling growth attributes of *S. macrophylla* differ in relation to the initial seedling age? (2) Do these variations in initial seedling age affect the survival and growth of outplanted seedlings in the field? The first and second questions will help in determining the optimal seedling production period in nurseries to achieve the desired morphological attributes which will enhance the survival and growth of outplanted seedlings.

8.2 Materials and Methods

8.2.1 Seed Collection, Preparation of Growing Medium, and Seedling Production

The detail information on the seed collection, preparation and initial characteristics of the growing medium as well as seedling production was mentioned in Chapter 7 of the study. Seedlings for three age groups (3-, 6-, and 9-month-old) were raised in the same conditions, in the Universiti Malaysia Sarawak (UNIMAS) forest research nursery located in Kota Samarahan, Sarawak, Malaysia from February-November 2015 and the detail information on the location and climatic data was mentioned in Chapter 3. A 5 g of chemical fertiliser (N: P: K = 10: 26: 10) per pot was applied as a top dressing of the polyethylene bags. The seedlings of the same cohorts were placed bare ground under a white transparent net. To maintain optimum soil moisture, seedlings were watered once a day at the beginning and then as required. Hand weeding was done regularly to prevent the growth of weeds on the surface of the polyethylene bags. The existing 24-month-old seedlings stock were produced from the same nursery with similar cultural practices. All the seedlings were exposed to direct sunlight for hardening prior to outplanting. Seedlings production was designed in such a way that four seedling age groups (3-, 6-, 9-, and 24-months-old) were available at the time of transplanting. Since this was the first study to investigate the effects of initial seedling age on the outplanting performance of *S. macrophylla*, seedlings at the range of 3-, 6-, 9-, and 24-months-old were selected for the purpose of this study.

8.2.2 Outplanting Site

Seedlings of *S. macrophylla* from all age groups were outplanted in 2015 at the Sampadi Forest Reserve Experimental Planting Sites (N01°03.953', E110°56.827'), located approximately 72 km southwest of Kuching City in Lundu, Sarawak, Malaysia. The

experimental site in the field was covered with grasses, shrubs, and pioneer trees. Therefore, prior to transplanting, all the vegetation in each planting line was slashed, cut to ground level, and completely removed. The topography of the planting site is of low undulating type with similar soil condition. The detail information on the location and climatic data was mentioned in Chapter 3. The major soil type in the planting site is derived from a mixture of sandstone, coarse-grained, and humult Ultisols which generally have low fertility (Perumal et al., 2015; 2017a; 2017b). Based on the Sarawak soil classification system and our preliminary study at the area, the morphological characteristics of the soils resemble Bako and Kayan soil series as a dominant unit in association with Saratok series and are categorised mainly under the soil group of Grey-White Podzolic soils interspersed with Red-Yellow Podzolic soils, and Arenaceous soils (Perumal et al., 2015; Department of Agriculture, Sarawak, 2018). According to the USDA-NRCS classification system, this soil group corresponds to Typic Paleaquults of Soil Taxonomy (Teng, 2004; Soil Survey Staff, 2014; Perumal et al., 2015). The initial surface and subsurface soil physicochemical characteristics of the experimental planting sites are presented in Table 8.1.

8.2.3 Experimental Design and Outplanting of Seedlings

In order to investigate the effects of initial seedling age on survival, growth attributes, and biomass production of *S. macrophylla* seedlings after 12, 24, and 42 months of outplanting, the field experimental planting site was divided into three blocks separated by 5 m, and each block was further divided into four plots of 50 m × 10 m, these were also separated from each other by 5 m strips (Figure 8.1). In each plot within each block, 20 seedlings of *S. macrophylla* from one age group (3, 6, 9, and 24 months) were planted in 5 m × 5 m spacing. During the lay-out planning for this experiment, *in-situ* site conditions such as similar

topography and existing vegetation were considered as to ensure the uniformity of the experimental sites for each treatment.

Table 8.1: Means and standard error of initial surface and subsurface soil physicochemical characteristics of the experimental planting sites at Sampadi Forest Reserve.

Soil Depth / Soil Physicochemical Properties		0-10 cm (Surface Soils)		30-40 cm (Subsurface Soils)	
		Mean $\pm$ S.E.	(min.-max.)	Mean $\pm$ S.E.	(min.-max.)
pH (H ₂ O)		4.63 $\pm$ 0.02	(4.19-5.07)	4.79 $\pm$ 0.01	(4.67-4.99)
pH (KCl)		3.59 $\pm$ 0.01	(3.46-3.82)	3.61 $\pm$ 0.01	(3.52-3.70)
EC ^a	(μ S cm ⁻¹)	57.4 $\pm$ 1.2	(35.1-91.1)	22.9 $\pm$ 0.6	(12.8-36.8)
Total C ^b	(g kg ⁻¹)	57.3 $\pm$ 1.0	(37.7-80.1)	33.7 $\pm$ 0.6	(14.3-42.4)
Total N ^c	(g kg ⁻¹)	2.46 $\pm$ 0.04	(1.53-3.47)	0.91 $\pm$ 0.03	(0.42-1.39)
CEC ^d	(cmol _c kg ⁻¹)	17.8 $\pm$ 0.3	(10.4-23.2)	15.4 $\pm$ 0.3	(7.0-19.2)
Exch. Ca ²⁺	(cmol _c kg ⁻¹)	0.74 $\pm$ 0.06	(0.10-2.01)	0.21 $\pm$ 0.02	(0.01-0.53)
Exch. Mg ²⁺	(cmol _c kg ⁻¹)	0.68 $\pm$ 0.03	(0.24-1.36)	0.14 $\pm$ 0.01	(0.04-0.29)
Exch. K ⁺	(cmol _c kg ⁻¹)	0.20 $\pm$ 0.02	(0.01-0.57)	0.14 $\pm$ 0.01	(0.01-0.49)
Exch. Al ³⁺	(cmol _c kg ⁻¹)	2.68 $\pm$ 0.11	(1.13-4.69)	3.38 $\pm$ 0.09	(2.26-4.66)
SUM ^e	(cmol _c kg ⁻¹)	1.79 $\pm$ 0.10	(0.41-3.81)	0.67 $\pm$ 0.03	(0.18-1.25)
Available P	(mg P kg ⁻¹)	15.2 $\pm$ 1.0	(0.2-33.4)	3.7 $\pm$ 0.4	(0.1-10.0)
Clay	(%)	48.8 $\pm$ 1.0	(28.0-60.2)	48.1 $\pm$ 0.8	(23.4-58.2)
Silt	(%)	40.7 $\pm$ 0.4	(32.4-48.3)	37.2 $\pm$ 0.5	(27.6-47.3)
Sand	(%)	10.5 $\pm$ 1.2	(0.5-39.7)	14.7 $\pm$ 1.0	(3.4-49.0)
Bulk density	(g mL ⁻¹)	0.88 $\pm$ 0.01	(0.72-1.04)	1.17 $\pm$ 0.02	(0.86-1.53)
Hardness	(J cm ⁻¹)	3.1 $\pm$ 0.1	(2.0-4.9)	8.3 $\pm$ 0.3	(3.9-14.7)

Means $\pm$ standard error, ^a EC: Electrical Conductivity; ^b Total C: Total Carbon; ^c Total N: Total Nitrogen; ^d CEC: Cation Exchange Capacity; ^e SUM: Sum of Exchangeable Bases (Ca, Mg, K, Na).

8.2.4 Data Collection and Analyses

At the time of transplanting, a 5 g of chemical fertiliser (N: P: K = 10: 26: 10) was applied in the planting hole sized approximately 12 cm in diameter and 15 cm in depth. A thin layer of soil was placed in the bottom of the planting hole between the roots of the planted seedlings and the fertiliser to prevent root burn.

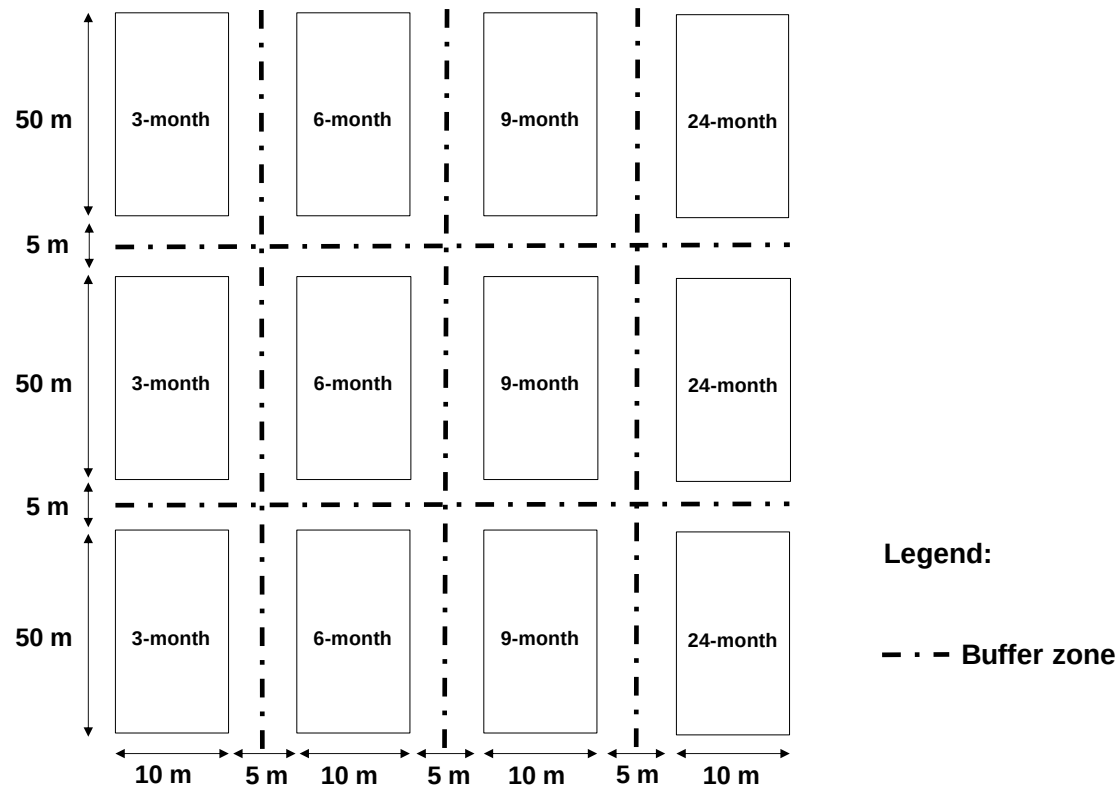


Figure 8.1: Lay-out of field experimental plots for planting *S. macrophylla* at Sampadi Forest Reserve experimental planting sites. 3, 6, 9, and 24 stand for age groups in the actual figure.

One month after transplanting, the shoot height and root collar diameter of all 60 seedlings from each age group were recorded. The measurements were repeated 12, 24, and 42 months after transplanting. Seedling shoot height and root collar diameter were measured following the methods of Wasli et al. (2014) and Perumal et al. (2017a). Survival percentages were calculated as the number of seedlings of the original 20 remaining alive for each block at the time of each measurement (12, 24, and 42 months after transplanting). Relative growth rate (RGR, hereafter) for shoot height and root collar diameter in the field were calculated for 20 individuals in each age group using the following equation (Kramer and Kozłowski, 1979):

$$RGR = \left(\frac{\ln X_2 - \ln X_1}{\Delta t} \right)$$

where X_1 and X_2 denote variables measured at the time of the first and second assessments, respectively and Δt is the time interval between the two measurements.

Prior to transplanting, the initial shoot, root, and total biomass including belowground biomass of all 60 seedlings from each age group were quantified using the allometric equations, and the formula are as follow (Kenzo, 2004; Hattori et al., 2013):

$$S. macrophylla: Y = 0.19X^{1.05}, R^2 = 0.96$$

where [Y (g) = Shoot biomass, X (cm³) = diameter² × height]

$$S. macrophylla: Y = 0.17X^{0.82}, R^2 = 0.91$$

where [Y (g) = Root biomass, X (cm³) = diameter² × height]

$$S. macrophylla: Y = 0.33X^{0.99}, R^2 = 0.97$$

where [Y (g) = Total biomass, X (cm³) = diameter² × height]

The allometric equations were also used for quantifying the shoot, root, and total biomass including the belowground biomass of the survived *S. macrophylla* seedlings after 12, 24 and 42 months of outplanting in the field from each age group.

The data on seedling growth attributes at planting, seedling survival for the field experiment, and outplanting trial was analysed using a one-way analysis of variance (ANOVA). For seedling after planting (outplanting trial), a one-way ANOVA was performed to determine whether shoot height, root collar diameter, RGR of shoot height and root collar diameter, and biomass production was significantly affected by initial seedling age. For the purpose of statistical analyses, each individual seedling was treated as a replicate of the

sampling unit and the experimental unit was the mean response from the sampling units for each treatment replication. In each analysis, when ANOVA was significant, statistically significant differences between means were identified using Tukey's Honestly Significant Difference (HSD) and Scheffe's Multiple Comparison tests. The coefficient of determination (R^2) was calculated to quantify relationships among initial seedling age variables. All statistical analyses were performed using Statistical Package for the Social Sciences (SPSS) (IBM, version 24.0 for windows) (Copyright: SPSS Inc., 2016).

8.3 Results and Discussion

8.3.1 Initial Seedling Growth Attributes

The effects of the initial seedling age on growth attributes of *S. macrophylla* seedlings at the time of planting varied. Morphologically, nearly all growth attributes and biomass production exhibited significant differences ($P < 0.05$) with respect to the period of nursery growth (Figure 8.2). The age at the time of transplanting affected shoot height ($F_{[3, 236]} = 466.503, P < 0.001$), root collar diameter ($F_{[3, 236]} = 73.069, P < 0.001$), total biomass ($F_{[3, 236]} = 155.155, P < 0.001$), and biomass allocation between roots and shoots (root to shoot ratio) ($F_{[3, 236]} = 128.801, P < 0.001$). The shoot height, root collar diameter, and total biomass of seedlings tended to increase with seedling age in the nursery and were significantly larger for 24-month-old than for 3-, 6-, or 9-month-old seedlings, except for root to shoot ratio (Figure 8.2). However, the root to shoot ratio of seedlings tended to decrease with increasing period of nursery growth.

Pearson correlation coefficients (Table 8.2) indicated that root collar diameter was most negatively and significantly correlated with root to shoot ratio followed by total biomass with root to shoot ratio and shoot height with root to shoot ratio. On the other hand,

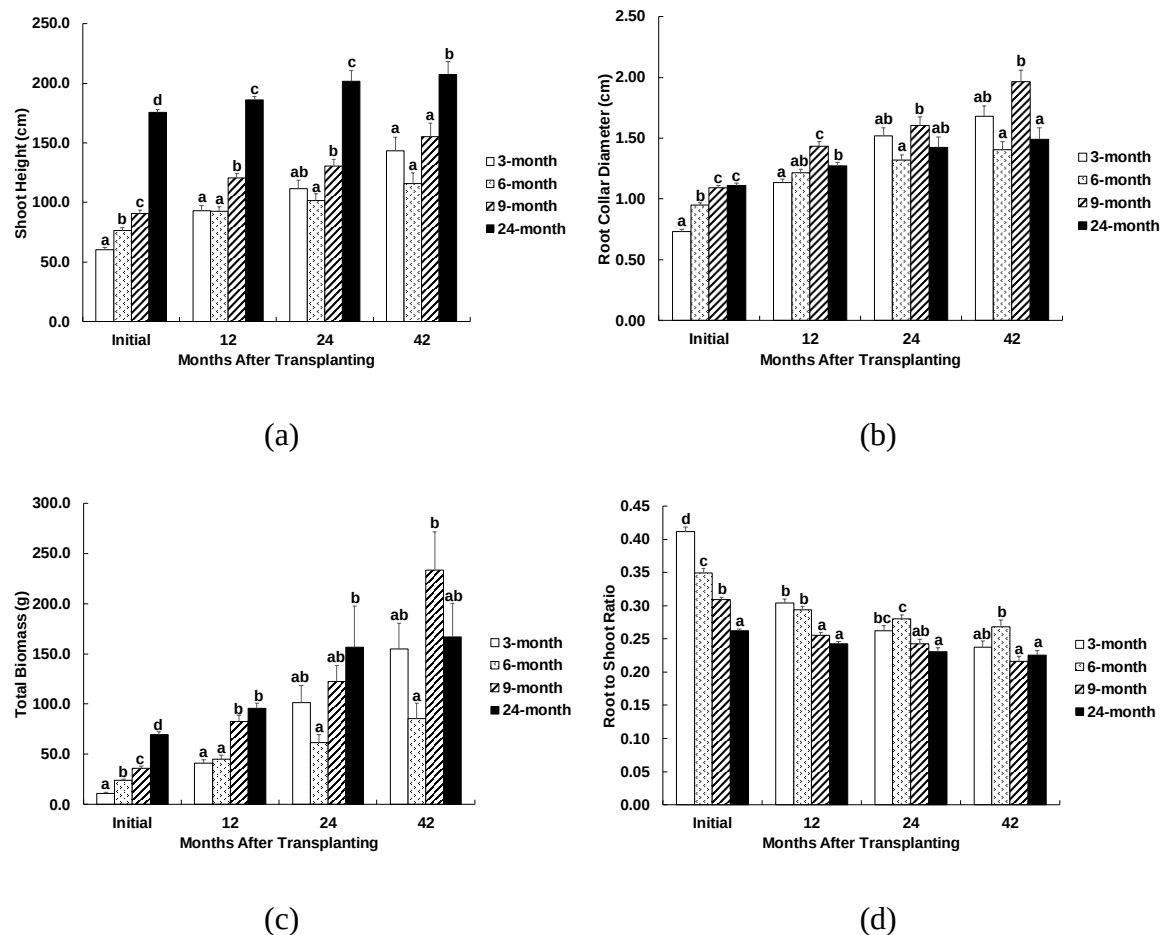


Figure 8.2: Initial seedling sizes of *S. macrophylla* differing in nursery age and effect of age at planting on (a) shoot height, (b) root collar diameter, (c) total biomass, and (d) root to shoot ratio of seedlings after 12, 24, and 42 months of outplanting. Bars are means and error bars are standard errors. Bars with different letters are significantly different at 5% level using Scheffe's Multiple Comparison test.

Table 8.2: Pearson correlation coefficients for the relationship among initial growth attributes of *S. macrophylla* seedlings (n = 240).

	Shoot height	Root collar diameter	Total biomass
Root collar diameter	0.594**		
Total biomass	0.888**	0.829**	
Root to shoot ratio	-0.806**	-0.903**	-0.855**

* Correlation is significant at the 0.05 level; ** Correlation is significant at the 0.01 level.

shoot height was most positively and significantly correlated with total biomass followed by root collar diameter with total biomass and shoot height with root collar diameter.

8.3.2 Performance of Outplanted Seedlings

Pooled mean survival rates overall declined from 61.7 to 44.6% after 12, 24, and 42 months of outplanting (Table 8.3). The survival rates of *S. macrophylla* seedlings varied and affected by initial seedling age in the field. After the first 12 months of transplanting, seedling field survival ranged from 46.7 to 73.3% and differed among initial seedling ages. The survival rate at 3-month-old transplanting age was significantly higher ($P < 0.05$) than 6-, 9-, and 24-month-old transplanting ages. However, there was no significant difference for survival rate between 6- and 9-month-old transplanting ages after 12 months of outplanting. At 24 months after outplanting, survival rates of 3-, 6-, and 9-month-old transplanting ages were significantly higher than the 24-month-old seedlings. However, after 42 months of outplanting, the field survival rate of 9-month-old seedling was significantly higher than others.

Table 8.3: Effect of age at planting on survival rate (%) of *S. macrophylla* seedlings after 12, 24, and 42 months of outplanting (mean $\pm$ S.E.).

Initial seedling age	Months after transplanting		
	12 months	24 months	42 months
3-month	73.3 $\pm$ 2.1 c	63.3 $\pm$ 1.7 b	46.7 $\pm$ 1.3 b
6-month	61.7 $\pm$ 0.8 b	56.7 $\pm$ 1.6 b	45.0 $\pm$ 1.8 b
9-month	65.0 $\pm$ 2.1 b	60.0 $\pm$ 2.4 b	53.3 $\pm$ 2.4 c
24-month	46.7 $\pm$ 1.2 a	41.7 $\pm$ 1.7 a	33.3 $\pm$ 1.1 a
Mean	61.7	55.4	44.6

Values are means $\pm$ standard error; values in the same column followed by different letters indicate significant differences among initial seedling age at 5% level using Tukey's Honestly Significant Difference (HSD) test.

The 24-month-old seedlings kept their shoot height dominance after 12, 24, and 42 months of outplanting. Likewise, seedlings of 6- and 9-month-old kept their shoot height dominance after 12 and 24 months, while the differences declined after 42 months of outplanting (Figure 8.2a). For example, differences in seedling shoot height were significant between 6- and 9-month-old after 12 and 24 months of transplanting, while no significant difference was found in the following 42 months after transplanting. Notwithstanding, there was no significant difference observed in shoot height between 3- and 6-month-old seedlings at 12, 24, and 42 months after outplanting. In general, shoot height tended to increase with seedling age, except for 6-month-old seedlings in this study.

Relative to shoot height, younger (3- and 6-month-old), as well as older (24-month-old) seedlings, lost their root collar diameter dominance more rapidly (Figure 8.2b). As early as in the first 12 months of outplanting, no significant difference was shown in root collar diameter between 3- and 6-month-old seedlings (Figure 8.2b). Similarly, after 24 and 42 months, differences were not significant among 3-, 6-, or 24-month-old seedlings. The root collar diameter was significantly higher and larger for 9-month-old seedlings than 6- and 24-month-old seedlings at 12 and 42 months after transplanting.

In terms of RGR of shoot height, significant difference was found in the first 12 months but not for 24 and 42 months after outplanting (Table 8.4). At 12 months after outplanting, 9-month-old seedlings had greater RGR in shoot height than 3-month-old seedlings, followed by 6- and 24-month-old seedlings. Meanwhile, the significance difference in RGR of root collar diameter was observed for 12, 24, and 42 months after outplanting (Table 8.4). At 12, 24, and 42 months after transplanting, 3-month-old seedlings displayed larger RGR in root collar diameter than 9-month-old seedlings, followed by 6- and 24-month-old seedlings.

Table 8.4: Effect of age at planting on relative growth rates of shoot height (RGR_{sh}: cm cm⁻¹ mo⁻¹) and root collar diameter (RGR_{cd}: cm cm⁻¹ mo⁻¹) of *S. macrophylla* seedlings after 12, 24, and 42 months of outplanting (mean ± S.E.).

Initial seedling age	RGR _{sh}			RGR _{cd}		
	12 months	24 months	42 months	12 months	24 months	42 months
3-month	1.88 ± 0.25 b	1.70 ± 0.29 a	1.67 ± 0.28 a	0.023 ± 0.002 b	0.028 ± 0.003 b	0.020 ± 0.002 b
6-month	0.83 ± 0.17 a	0.81 ± 0.16 a	0.86 ± 0.18 a	0.017 ± 0.002 ab	0.014 ± 0.002 a	0.010 ± 0.001 a
9-month	1.91 ± 0.23 b	1.31 ± 0.22 a	1.31 ± 0.26 a	0.022 ± 0.002 b	0.018 ± 0.003 a	0.018 ± 0.002 b
24-month	0.40 ± 0.21 a	0.86 ± 0.35 a	0.72 ± 0.25 a	0.012 ± 0.001 a	0.012 ± 0.003 a	0.009 ± 0.002 a

Values are means ± standard error; values in the same column followed by different letters indicate significant differences among initial seedling age at 5% level using Scheffe's Multiple Comparison test.

At 12 months after transplanting, total biomass tended to increase with seedling age and was significantly larger for 9- or 24-month-old than 3- or 6-month-old seedlings (Figure 8.2c). However, at 24 and 42 months, significant differences were only found between 6- and 24-month-old seedlings, as well as between 6- and 9-month-old seedlings, respectively. Total biomass for 9-month-old was the largest than the others at 42 months after transplanting.

On the other hand, biomass allocation of seedlings between roots and shoots, as determined by the root to shoot dry mass ratio after 12, 24, and 42 months of outplanting vary significantly between age groups (Figure 8.2d). The root to shoot ratio for 9 and 24-month-old transplanting ages were significantly lower than 3- or 6-month-old transplanting ages after 12 months in the field (Figure 8.2d). The differences declined except between 6-, 9-, or 24-month-old seedlings at 24 and 42 months after transplanting.

8.3.3 Effects of Initial Seedling Age on Survival after Outplanting

Under the conditions of this study, all morphological characters of *S. macrophylla* seedlings varied significantly and exhibited a response to seedling age (young and old seedlings) at planting (Figure 8.2). Since the production of high-quality seedlings in a reasonable time is the ultimate goal much desired by nursery personnel, modifications of the current nursery practices such as lack of mycorrhizal inoculation are required to produce seedlings with the desired morphological and physiological attributes for improved field performance (Zida et al., 2008).

Following the first 12 and 24 months after outplanting at Sampadi Forest Reserve experimental sites, field survival was considered moderately high for 3-, 6-, and 9-month-old nursery age groups, but was slightly low for the 24-month-old nursery age group (Table

8.3). However, at 42 months after outplanting, 9-month-old seedling age depicted the highest survival rate as compared to the other nursery age groups. This could be related to the intact root system of container-grown seedlings, which resulted in lower resistance to water flow through the soil-plant-atmosphere continuum (Grossnickle, 2005). Previous long-term monitoring study by Hattori et al. (2013) in Niah Forest Reserve, Sarawak reported 43.9% and 52.3% of 12-month-old *S. macrophylla* seedling survival following 81 months after outplanting in secondary and logged forests, respectively. Notwithstanding, higher survivability is usually reported in seedlings planted under secondary and logged forests; for example, 37.5% to 70.0% of *Shorea parvifolia* seedlings were alive after 24 months in Indonesian secondary forests where line planting techniques have been used (Ådjers et al., 1995), and more than 94% of *Dryobalanops aromatica* and *S. parvifolia* seedlings survived after 22 months in a secondary forest of Sampadi Forest Reserve and Balai Ringin Protected Forest in Sarawak (Vincent & Davies, 2003). In contrast, the high survivability of *S. parvifolia* recorded in previous studies may have subsequently declined after more than 2 years after outplanting, since only 11.8% and 25.7% of the seedlings remained 81 months after outplanting in the secondary and logged forests of Niah Forest Reserve (Hattori et al., 2013).

Survival in the field, however, was generally high for 3-, 6-, and 9-month-old nursery age groups, probably due to the protection of the polybag (container) as well as the degree of disturbance to the root system during storage, lifting, transportation, and planting is much lower for container-grown seedlings than bare-root seedlings (Liu, 1999; Wilson et al., 2007; Zida et al., 2008). Consequently, container-grown seedlings experience lower plant water stress after transplantation and have better survival in the field than bare-rooted seedlings. On the contrary, a high degree of disturbance to the root system during storage, lifting,

transportation, and planting had probably resulted in a low survival rate for 24-month-old seedlings. As for the case of this study, the field survival rate of seedlings from 6-month-old age group was apparently much lower and decreased rapidly than 3- and 9-month-old seedlings (Table 8.3) which probably due to the site-specific environmental factors thus caused the mortality of the planted seedlings (Hitch et al., 1996). Studies by Garau et al. (2009) indicated that small-sized seedlings were more sensitive to site environments and site preparation and that may be the case for the lower survival of 6-month-old seedlings. Large mass (Johansson et al., 2007; Renou-Wilson et al., 2008) can promote the field performance of seedlings. The large total biomass might explain why 9-month-old seedlings had greater long-term survival after 42 months of outplanting in this study.

8.3.4 Effects of Initial Seedling Age on Growth after Outplanting

In terms of growth attributes, younger (3- and 6-month-old) and older (9- and 24-month-old) seedlings of *S. macrophylla* were different at the time of planting (Figure 8.2). Nonetheless, these variations in initial seedling sizes at the time of planting still persist in the field after 12, 24, and 42 months of outplanting for all the seedling growth attributes, except for variation in seedling ages for relative growth rate of shoot height after 24 and 42 months (Figure 8.2; Table 8.4). For 3-month-old seedlings, higher RGR in both shoot height and root collar diameter was found after outplanting (Table 8.4). The possible explanation is that small seedlings suffered less transplant shock when outplanted (Close & Beadle, 2003; Close et al., 2010), or small seedlings displayed higher maximum potential photochemical activity when established (Renou-Wilson et al., 2008). Considering the field performance, the 3-month-old seedlings will shorten the culture period in the nursery and are easier to handle for planting because of their small size. Thus, the seedlings can be kept as a planting material

in the nursery for reforestation programs especially during irregular flowering or unpredictable fruiting intervals of *S. macrophylla*. Previous study by Hattori et al. (2013) in Niah Forest Reserve reported that *S. macrophylla* seedlings had a relatively lower growth rate of height ($0.105 \text{ cm cm}^{-1} \text{ year}^{-1}$) and diameter ($0.124 \text{ mm mm}^{-1} \text{ year}^{-1}$) than *D. beccarii* ($0.316 \text{ cm cm}^{-1} \text{ year}^{-1}$, $0.328 \text{ mm mm}^{-1} \text{ year}^{-1}$), *S. parvifolia* ($0.328 \text{ cm cm}^{-1} \text{ year}^{-1}$, $0.308 \text{ mm mm}^{-1} \text{ year}^{-1}$) and other *Shorea* species, respectively. In open areas of Borneo, tree height growth of planted dipterocarp species such as *S. macrophylla* (461 cm after 72 months (Lee et al., 1997), *S. ovata* (450 cm after 60 months) (Alias et al., 1998), and 11 other dipterocarp species (320 to 580 cm after 60 months) (Meguro & Miyawaki, 1997) were also reported.

Based on this study, in general, higher RGR in shoot height and root collar diameter for 9-month-old seedlings after outplanting was also found, questioning the conventional recommendation that larger seedlings make the best planting stock (South et al., 2005b; McGrath & Duryea, 1994). In many studies, larger seedlings tend to maintain an advantage in size over time compared to smaller seedlings (Rose & Ketchum, 2003; Haase et al., 2006), partly because of the ability to grow competing vegetation (South et al., 2005b), while others report that differences decrease after a couple of years (South et al., 2001; Olliet et al., 2005). In addition, the general pattern observed in this and other studies was also that when seedlings are properly planted in large diameters (morphologically improved), they typically grow better than smaller seedlings (South et al., 1993a, 2005b). It could be deduced that seedling performance is diameter related and seedlings with large diameters tend to survive and grow better than seedlings with small diameters (South et al., 1993a; McGrath & Duryea, 1994). According to Simpson and Ritchie (1997), one reason that larger seedlings display greater growth is that the large seedlings soon after planting produce many roots.

In this study, we found that all younger and older *S. macrophylla* seedlings had a

biomass allocation pattern in favour to the general expectations of a balanced root system (root to shoot dry mass ratio < 2.0 g/g) and continued to maintain this pattern in the field (Figure 8.2d). In general, these seedlings had higher growth capability and were able to withstand the adverse conditions (periodic inundation) in planting sites due to the adequate root system that did not impede the growth of the plant. Although we do not quantify, we observed seedling shoot dieback due to the flooding effect which had occurred in January 2016. In certain instances, a high root to shoot ratio is beneficial for seedling growth. For example, under conditions where a wet season precedes a dry summer, seedlings defined as productive phenotypes (i.e., large seedlings with high root to shoot ratio and fertility) have higher growth capability (Oliet et al., 2005; Cuesta et al., 2010) with larger seedlings becoming better established during the wet season (Villar-Salvador et al., 2012, 2015).

Seedling shoot height at planting can influence growth because taller seedlings keep their height advantage over time (Pinto, 2011; Pinto et al., 2015). This shoot height advantage is beneficial on sites with competing vegetation (Morrissey et al., 2010; Thiffault et al., 2014) in part because they outgrow competitors (South et al., 2005c). Seedlings with greater initial height can subsequently develop greater shoot-system due to a higher number of branches, buds, and foliage in hardwoods (del Campo et al., 2010). Consequently, such seedlings have a greater photosynthetically active surface area (Grossnickle, 2000; Luis et al., 2009). Furthermore, according to Balneaves (1989) and Mason (2001), planting of larger seedlings can lead to better growth at restoration sites for up to 15 years after planting because larger seedlings have a higher foliar mass which allow for greater seedling photosynthetic capacity.

Grossnickle and MacDonald (2018) mentioned that initial root collar diameter is deliberated the best morphological attribute to forecast future growth since it correlates

positively with seedling weight (overall seedling size) and root system size at the end of nursery development (Rawat & Singh, 2000; Binotto et al., 2010), as well as across species and stocktypes. Approximately 91% of studies reported a positive relationship between initial root collar diameter and post-planting growth which has been documented for 4, 5 (Aphalo & Rikala, 2003; Howell & Harrington, 2004), and 17 years (Dierauf & Garner, 1996) after planting. In addition, the initial seedling size can have a long-term effect on field growth. For example, seedlings that were larger at planting had greater height and diameter 32-37 years after planting (Jäghagen & Albrektson, 1996).

As to ensure better field performance of *S. macrophylla* seedlings for forest restoration purpose, the results from this study suggested that the seedlings produced at 3-, 6-, and 9-month-old are beneficial to be kept as planting material until the initiation of transplantation in rehabilitation programs in Sarawak. In several cases, dipterocarp seedlings will have to be kept over a much longer period of time before transplantation, depending on the rehabilitation programs (Irino et al., 2005). In that case, 24-month-old seedling will be useful as well as during irregular flowering and unpredictable fruiting intervals of *S. macrophylla*. Previous study by Irino et al. (2005) concluded that *Dryobalanops lanceolata* seedlings displayed a sound growth without additional fertilisation, even though the seedling were kept in the nursery for 18 months after controlled-release fertiliser (CRF) application.

Numerous studies have demonstrated and discussed that nursery cultural practices including types of fertilisations strongly have a substantial influence on seedling quality and performance after outplanting (Liu et al., 2000; Gao et al., 2007; Wang et al., 2007; Li et al., 2011, 2012; Takoutsing et al., 2012). However, most of these studies did not combine nursery cultivation treatments with planting site conditions. Field trials are essential for validating the suitability of nursery techniques and the identification of the seedling

functional attributes which forecast outplanting performance (Andivia et al., 2018). Takoutsing et al. (2014) suggested that the only way to fully comprehend the behaviours of seedling promoted by nursery techniques and its productivity is to consider the outplanting site condition since nursery cultural practices vary by species, nursery, and outplanting environments.

CHAPTER 9

CONCLUSION AND RECOMMENDATIONS

9.1 Conclusion

Information on the current status of the soil properties under a rehabilitated forest of various stand ages is vital in order to know the suitability of the site which had been planted with *S. macrophylla* for reforestation activities in comparison to an adjacent secondary forest. Based on Chapter 4 of this study, the preliminary findings indicated that the soils in the study area consisted of sand, silt, clay, and loam texture in the horizons of the soil profiles. In addition, the soils in the study area comprised of mainly Grey-White Podzolic soils which derived from the combination of sandstone, coarse-grained, humult ultisols, and sandy residual parent material. Nevertheless, such soil indicates the existence of Bako soil series as a dominant unit in association with Saratok series, in which corresponds to Typic Paleaquults of Soil Taxonomy by USDA-NRCS Classification. Generally, in terms of the soil physicochemical properties, the soils at the reforestation sites especially in SM96 was slightly at the range of secondary forest due to the recovering pool of soil in order to reach the value of the typical secondary forest.

In Chapter 5, a considerable tree growth was revealed based on the assessment of survivorship and tree growth performance of *S. macrophylla* after enrichment planting under various stand ages which clarified the efficiency of line planting technique used in Sampadi Forest Reserve. Nonetheless, high survival rate ($\geq 80\%$) in SM96, SM97, and SM98 which associated with considerable growth in terms of diameter and height of *S. macrophylla* could be due to the good adaptability and survivability of this species which can grow under certain soil condition or competition for light between planted trees and naturally grown vegetation

which was undisturbed with the planting line in this study. The findings implied that *S. macrophylla* was suitable for forest restoration purpose and the positive outcome could be achieved from this reforestation effort on the long run.

Based on the findings in Chapter 6, the assessment on the status of soil physicochemical properties showed that the soil properties are significantly different between the rehabilitation sites (SM96, SM97, SM98, and SM99) and secondary forest (SF). Generally, the soils in rehabilitation sites and secondary forest of Sampadi Forest Reserve could be categorised as strongly acidic in nature, pH (H₂O) values of less than 5.50 with poor soil exchangeable bases, and low nutrient status at surface and subsurface soil layers. The soils were relatively sandy, ranging from sandy clay loam to sandy clay in texture. Soil total carbon and total nitrogen in the secondary forest were significantly higher than those of the rehabilitation sites, showing that a large pool of fresh organic matter was derived from the above vegetation in the surface and subsurface soils. Principal Component Analysis (PCA) generated three most significant components which explained about 76.3% of the total variability and each component portrays a series of variables which simplifies the analysis and interpretation. The first component score (PC1) represents phosphorus content, soil acidity, and soil texture. Soil organic matter constituent and cation retention capacity represent PC2, whereas available nutrient represents PC3. Pearson correlation analysis indicated that Soil Fertility Index (SFI) was highly correlated with PC1 score, diameter at breast height (DBH), height, and survival of the planted *S. macrophylla* trees at surface soils, indicating the applicability of SFI as an index to estimate and quantify soil fertility and site quality under line planting technique in the present study. For practical purposes, it can be deduced that the SFI can be used as an index to assess the difference in growth of planted trees caused by variability and heterogeneity of soil fertility levels of degraded forestland

within a site. Notwithstanding, the results also showed that there was a strong association between soil available phosphorus with tree growth parameters indicating that soil available phosphorus is a better indicator than SFI in the present study.

As for the seedling quality assessments in Chapter 7, different types of nursery fertilisations revealed significant differences in morphological quality attributes of *S. macrophylla* seedlings at the end of nursery growing season (270 DAS). All types of fertilisers (CF, CIRF, and JF) are beneficial in raising the seedlings in the nursery. In particular, seedlings treated with jellyfish fertiliser was significantly higher than chemical and controlled-instant release fertilisers for all the morphological quality attributes, except for root to shoot ratio. Notwithstanding, findings from the present study also revealed that *S. macrophylla* seedlings from all the treatments meet the general expectations of a balanced root to shoot ratio values ($RS < 2$) and the seedlings raised in the nursery were of sub-optimal quality.

Nevertheless, the present findings from Chapter 8 found out that all growth attributes of *S. macrophylla* seedlings differed in relation to the initial seedling age. Initial seedling age (3-, 6-, 9-, and 24-month-old) at the time of planting affect the survival rate of transplanted seedlings. Pooled mean survival rates overall declined from 61.7 to 44.6% after 12, 24, and 42 months of outplanting. The survival rate at 3-month-old transplanting age was significantly higher than 6-, 9-, and 24-month-old transplanting ages. Nonetheless, initial seedling age at the time of planting had effects on the subsequent outplanting performance (shoot height, root collar diameter, relative growth rates of shoot height and root collar diameter, total biomass, and root to shoot ratio) of *S. macrophylla* seedlings. It was also concluded that, seedlings produced at 3-, 6-, and 9-month-old are beneficial to be kept as planting material until the initiation of transplantation in rehabilitation programs at Sarawak.

The 24-month-old seedling will be useful especially during irregular flowering and unpredictable fruiting intervals of *S. macrophylla* in the tropics.

It is hoped that all the scientific information and findings from this study would be very useful as guidelines for forest managers and nursery practitioners especially from Forest Department of Sarawak as well as policymakers to initiate and undertake enrichment planting in the State forest reserves as they meet the forest restoration set standards.

9.2 Recommendations for Future Research

Based on this study, it can be further continued with other plots in the reforestation area in order to get more information on soil morphological, physicochemical, and mineralogical properties for the recovery of the degraded soil ecosystem. Further research will be more valuable to find out if there are any other tree species that can survive under the same type of soil such as *S. macrophylla*.

It is recommended that *S. macrophylla* can be as one of the choices of planting species for current and future reforestation purpose since it was able to survive periodic inundation as reported in this study. Thus, further detailed studies are required in order to find out other environmental factors which could affect the survivorship and growth performance of *S. macrophylla* under line planting system in the humid tropics of Sarawak.

Consequently, it is suggested that, in future, further comprehensive studies on other environmental factors including soil biological properties which might influence the tree growth performance should be implemented. In addition, early establishment of experimental reforestation at nursery and field trials should be emphasised in order to obtain the initial data on seedling growth performance prior to outplanting. While defining the appropriate seedling stocktype to meet the needs that can be achieved through the variety of

methods, including the Target Plant Concept, an understanding of the interplay of nursery production techniques and factors influencing outplanting sites is necessary to ensure forest restoration is most effective.

Therefore, a holistic evaluation of stock quality requires the integration of both morphological and physiological attributes of seedlings that provides a more effective appraisal of the fitness of seedlings to become established for field planting. Since most studies did not combine nursery techniques with planting site conditions and limited research has been done on the seedling quality of indigenous species in Malaysia, development of species and site-specific targets for seedling shoot and root system quality assessment is required and subsequently tested as to ensure they meet the set standards.

As a follow up to this study, permanent sampling plots (PSPs) in the restoration area should be set up in order to see the changes of seedling growth pattern over time. Further experimental study is necessary to investigate other morphological and physiological attributes that could improve outplanting performance in the tropical forest rehabilitation area of Sarawak, Malaysia. A good understanding of the interaction between seedling morphological and physiological status and how this affects survival and growth in the field is required. In addition, long-term monitoring period of *S. macrophylla* trees and seedlings growth are required as to draw up a solid conclusion across various experimental treatments, site conditions, and species.

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APPENDICES

Appendix 1: View of the study site: Sampadi Forest Reserve, Lundu, Sarawak. GPS: (N01°34'13''E109°53'12'').



Appendix 2: Soil profile description of the study sites in Sampadi Forest Reserve, Lundu.

Profile No.: 1 (SM96)

Location: N01° 30'15.0", E109° 55'00.3"

Land use or vegetation: Forest rehabilitation with
S. macrophylla planted
in 1996

Slope gradient: 11°

Weather: Fine, sunny

Soil name: Grey-White podzolic soil

Date of Survey: 13/08/2013

Erosion: Slightly

Ground water: None

Drainage: None

Parent material: residual

Horizon	Depth (cm)	Description
O	0 - 3	Litterfall from dead leaves of <i>Shorea macrophylla</i> and mainly pioneer tree species
A	3 - 13	10YR5/6 (yellowish brown); moist; sandy clay loam to clay loam; moderate medium subangular blocky structure; friable; slightly sticky, plastic; very fine to medium common roots; common subangular fine gravel rock fragment; no mottling; medium level of organic matter; penetrometer 17 mm; few charcoal; gradual wavy boundary to
AB	13 - 30	10YR6/8 (brownish yellow); moist; sandy clay loam to clay loam; moderate medium subangular blocky structure; friable; slightly sticky, slightly plastic; fine few roots; common subangular fine gravel rock fragment; no mottling; medium level of organic matter; penetrometer 21 mm; very few charcoal; gradual wavy boundary to
B ₁	30 - 52	10YR7/6 (yellow); moist; clay loam; strong coarse subangular blocky structure; friable, sticky, plastic; very fine few roots; few subangular fine gravel rock fragment; no mottling; low level of organic matter; penetrometer 22 mm; diffuse wavy boundary to
B ₂	52 - 70	10YR6/4 (light yellowish brown); moist; sandy clay loam; strong coarse subangular blocky structure; friable; sticky, very plastic; fine few roots; few subangular fine gravel rock fragment; no mottling; low level of organic matter; penetrometer 29 mm; diffuse wavy boundary to

Appendix 2 continued.

Profile No.: 2 (SM97)

Location: N01° 30'12.0", E100° 54'56.0"

Land use or vegetation: Forest rehabilitation with
S. macrophylla planted
in 1997

Slope gradient: 7°

Weather: Cloudy

Soil name: Grey-White podzolic soil

Date of Survey: 21/11/2012

Erosion: Slightly

Ground water: None

Drainage: None

Parent material: residual

Horizon	Depth (cm)	Description
O	0 - 3	Litterfall from dead leaves of <i>Shorea macrophylla</i> and mainly pioneer tree species
A	3 - 12	10YR5/4 (yellowish brown); moist; clay loam; moderate medium subangular blocky structure; friable; sticky; plastic; fine common roots; no rock fragment; no mottling; medium level of organic matter; penetrometer 14 mm; diffuse smooth boundary to
AB	12 - 21	10YR6/4 (yellowish brown); moist; clay; moderate medium subangular blocky structure; friable; sticky, very plastic; fine many roots; no rock fragment; no mottling; low level of organic matter; penetrometer 16 mm; gradual wavy boundary to
B	21 - 70	10YR5/6 (brownish yellow); moist; clay; moderate to strong medium subangular blocky structure; friable; very sticky, very plastic; very fine common roots; no rock fragment; no mottling; low level of organic matter; penetrometer 18 mm; clear smooth boundary to

Appendix 2 continued.

Profile No.: 3 (SM98)

Location: N01° 30'12.1", E109° 54'54.8"

Land use or vegetation: Forest rehabilitation with
S. macrophylla planted
in 1998

Slope gradient: 9°

Weather: Fine, sunny

Soil name: Grey-White podzolic soil

Date of Survey: 19/12/2012

Erosion: Slightly

Ground water: None

Drainage: None

Parent material: residual

Horizon	Depth (cm)	Description
O	0 - 3	Litterfall from dead leaves of <i>Shorea macrophylla</i> and mainly pioneer tree species
A	3 - 12	10YR5/4 (yellowish brown); moist; loamy sand; moderate medium granular structure; friable; slightly sticky, plastic; fine to medium many roots; no rock fragment; no mottling; medium level of organic matter; penetrometer 15 mm; clear wavy boundary to
AB	12 - 25	10YR5/6 (brownish yellow); moist; sandy loam; moderate medium subangular blocky structure; friable; sticky, plastic; fine common to medium roots; no rock fragment; no mottling; low level of organic matter; penetrometer 18 mm; gradual wavy boundary to
B ₁	25 - 46	10YR6/8 (brownish yellow); moist; silty clay loam; moderate medium subangular blocky structure; friable; sticky, very plastic; very fine to fine few roots; no rock fragment; no mottling; low level of organic matter; penetrometer 20 mm; gradual wavy boundary to
B ₂	46 - 70	10YR6/6 (brownish yellow); moist; clay loam; moderate medium subangular blocky structure; friable; very sticky, very plastic, very fine few roots; no rock fragment; no mottling; low level of organic matter; penetrometer 21 mm; diffuse wavy boundary to

Appendix 2 continued.

Profile No.: 4 (SM99)

Location: N01° 30'12.1", E109° 52'54.3"

Land use or vegetation: Forest rehabilitation with
S. macrophylla planted
in 1999

Slope gradient: 12°

Weather: Fine, sunny

Soil name: Grey-White podzolic soil

Date of Survey: 19/12/2012

Erosion: Slightly

Ground water: None

Drainage: None

Parent material: residual

Horizon	Depth (cm)	Description
O	0 - 1	Leaf litter from dead leaves of <i>Shorea macrophylla</i> and mainly pioneer tree species
A	1 - 20	10YR5/6 (yellowish brown); moist; loamy sand; moderate medium granular structure; friable; sticky, plastic; fine to medium many roots; no rock fragment; no mottling; medium level of organic matter; penetrometer 14 mm; clear wavy boundary to
B ₁	20 - 48	10YR7/4 (very pale brown); moist; loam; moderate medium subangular blocky structure; friable; sticky, very plastic, fine to very fine few roots; no rock fragment; no mottling; low level of organic matter; penetrometer 18 mm; diffuse wavy boundary to
B ₂	48 - 70	10YR6/4 (light yellowish brown); moist; silty clay loam; moderate to strong medium subangular blocky structure; friable; very sticky, very plastic; no roots; no rock fragment; no mottling; low level of organic matter; penetrometer 19 mm; diffuse wavy boundary to

Appendix 2 continued.

Profile No.: 5 (SF)
Location: N01° 30'26.2", E109° 58'56.7"
Land use or vegetation: Secondary forest
Slope gradient: 18°
Weather: Fine, sunny
Soil name: Grey-White podzolic soil

Date of Survey: 06/08/2013
Erosion: None
Ground water: None
Drainage: None
Parent material: residual

Horizon	Depth (cm)	Description
O	0 - 4	Litterfall
A	4 - 21	10YR5/6 (yellowish brown); moist; clay loam; moderate medium granular structure; friable; slightly sticky, slightly plastic; fine many roots; no rock fragment; no mottling; medium level of organic matter; penetrometer 14 mm; clear wavy boundary to
AB	21 - 33	10YR6/4 (light yellowish brown); moist; clay; moderate medium subangular blocky structure; friable; sticky, plastic, fine to very fine few roots; no rock fragment; no mottling; low level of organic matter; penetrometer 15 mm; diffuse wavy boundary to
B	33 - 70	10YR6/8 (brownish yellow); moist; clay; moderate medium subangular blocky structure; friable; very sticky, very plastic; no roots; no rock fragment; no mottling; low level of organic matter; penetrometer 20 mm; abrupt wavy boundary to

Appendix 3: Inventory form.

Locality:

Date:

Plot Number:

Plot size:

Species:

Planting year:

Assessed by:

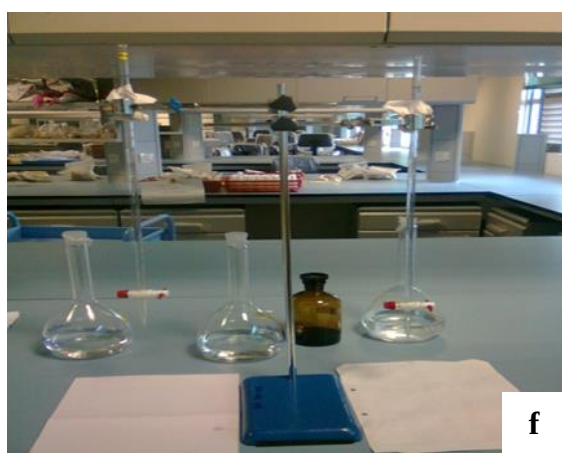
Age:

Planting distance:

GPS location:

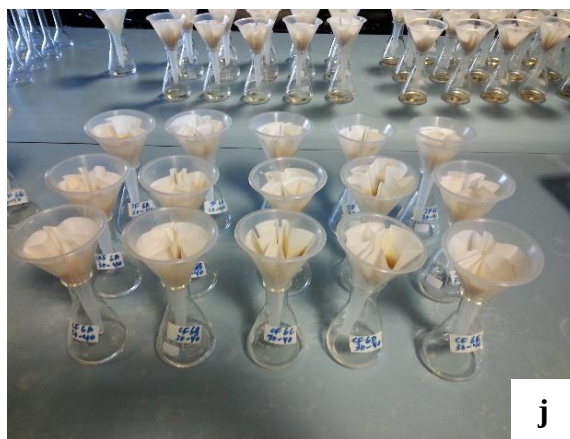
Tree No.	Diameter at Breast Height (cm)	Height (m)	Remarks
A11			
A12			
A13			
A14			
A15			
A21			
A22			
..			
..			
..			
..			
..			
..			
..			
..			
..			

Appendix 4: Soil physicochemical analyses conducted in Laboratory of Environmental Soil Science, Faculty of Resource Science and Technology, Universiti Malaysia Sarawak (UNIMAS).



Soil sample preparation for grinding; (b) Soil bulk density analysis; (c) Soil texture/ particle size analysis; (d) 10 ml of soil samples pipetted from 1 L cylinder for oven-dry at 105°C; (e) Soil filtrate collected for exchangeable Al analysis; (f) Soil exchangeable Al analysis using acid-base titration method.

Appendix 4 continued.



(g) Soil exchangeable bases analysis using Atomic Absorption Spectrophotometer (AAS); (h) Soil cation exchange capacity (CEC) analysis using steam distillation; (i) Soil organic matter analysis using loss on ignition method; (j) Soil filtrate collected for available phosphorus determination; (k) Soil particle density analysis; (l) Soil nitrogen analysis using Kjeldahl acid digestion method.

Appendix 5: Seed collection, germination, and seedling production of *S. macrophylla* in Universiti Malaysia Sarawak (UNIMAS) forest research nursery.



Appendix 5 continued.



Appendix 6: Outplanting of *S. macrophylla* seedlings and field sampling in Sampadi Forest Reserve Experimental Planting Sites.



Appendix 6 continued.



Appendix 6 continued.



Appendix 7: List of journal publications.

- Perumal, M., Wasli, M.E., Ho, S.Y., Lat, J., & Sani, H. (2015). Soil morphological and physicochemical properties at reforestation sites after enrichment planting of *Shorea macrophylla* in Sampadi Forest Reserve, Sarawak, Malaysia. *Borneo Journal of Resource Science and Technology*, 5(2), 28-43.
- Perumal, M., Wasli, M.E., Ho, S.Y., Lat, J., & Sani, H. (2017a). Survivorship and growth performance of *Shorea macrophylla* (de Vriese) after enrichment planting for reforestation purpose at Sarawak, Malaysia. *OnLine Journal of Biological Sciences*, 17(1), 7-17.
- Perumal, M., Wasli, M.E., Ho, S.Y., Lat, J., & Sani, H. (2017b). Association between soil fertility and growth performance of planted *Shorea macrophylla* (de Vriese) after enrichment planting at rehabilitation sites of Sampadi Forest Reserve, Sarawak, Malaysia. *International Journal of Forestry Research*, 2017, Article ID 6721354, 16 pages, <https://doi.org/10.1155-5/2017/6721354>.
- Perumal, M., Wasli, M.E., & Ho, S.Y. (2019). Influences of inorganic and organic fertilizers to morphological quality attributes of *Shorea macrophylla* seedlings in a tropical nursery. *Biodiversitas Journal of Biological Diversity*, 20(8), 2110-2118.

Appendix 8: List of indexed proceedings.

- Perumal, M., Wasli, M.E., Sani, H., Said, A., & Nahrawi, H. (2012). Growth performance of planted *Shorea macrophylla* under line planting technique. In: Wasli, M.E., Sani, H., Fasihuddin, B.A., Mohamad, S., Lim, P.T., Lee, K.S., & Sidi, M. (Eds.), *Proceeding: Natural Resources in the Tropics: Sustaining Tropical Natural Resources Through Innovations, Technologies and Practice*. Universiti Malaysia Sarawak. pp. 380-387.
- Perumal, M., Wasli, M.E., Sani, H., & Ho, S.Y. (2013). Morphological and physicochemical properties of the soil planted with *Shorea macrophylla* at Sampadi Forest Reserve, Sarawak. In: *Proceeding: The 7th International Symposium on Kuroshio Science-Enhancing Management and Conservation of Kuroshio Region through Harmony between People and Environment*. Pontianak, West Kalimantan, Indonesia, 21-23 November 2013.
- Perumal, M., Wasli, M.E., & Lat, J. (2016). Effects of enrichment planting on the soil physicochemical properties at reforestation sites planted with *Shorea macrophylla* de Vriese in Sampadi Forest Reserve, Sarawak, Malaysia. In: Sakai, S., Pungga, R.S., Meleng, P., & Itioka, T. (Eds.), *Proceeding: International Symposium on Frontier in Tropical Forest Research: Progress in Joint Projects between the Forest Department Sarawak and the Japan Research Consortium for Tropical Forests in Sarawak*. Forest Department Sarawak. pp. 19-29.
- Perumal, M., Wasli, M.E., & Lat, J. (2016). Estimating soil fertility status using soil quality indices at reforestation sites in Sampadi Forest Reserve, Sarawak, Malaysia. In: Jusoh, I., Ipor, I., Puad, A.S.A., & Hassan, R. (Eds.), *Proceeding: The 2nd Regional*

Taxonomy and Ecology Conference. Universiti Malaysia Sarawak, Kota Samarahan, Sarawak. pp. 275-287.

Perumal, M., Wasli, M.E., Sani, H., Lat, J., & Ho, S.Y. (2016). Effects of selected soil physical characteristics on the growth and survivability of planted *Shorea macrophylla* (de Vriese) along riverbanks of Batang Kayan Ulu, Lundu, Sarawak. In: Arshad, A.M., Haruna, A.O., Abdullah, R., Ishak, C.F., Sung, C.T.B., Vijayanathan, J., & Sembok, W.Z.W. (Eds.), *Proceedings: Soil Science Conference of Malaysia: Soil Improvement for Sustainable Crop Production*. Malaysian Society of Soil Science and Universiti Malaysia Terengganu, Kuala Terengganu, Terengganu. pp. 310-315.