DEVELOPMENT OF NEW TECHNIQUES OF SEED STORAGE AND DIRECT SEEDING OF NATIVE TREE SPECIES FOR TROPICAL FOREST RESTORATION

PANYA WAIBOONYA

DOCTOR OF PHILOSOPHY

IN BIOLOGY

GRADUATE SCHOOL

CHIANG MAI UNIVERSITY

JULY 2017

DEVELOPMENT OF NEW TECHNIQUES OF SEED STORAGE AND DIRECT SEEDING OF NATIVE TREE SPECIES FOR TROPICAL FOREST RESTORATION

PANYA WAIBOONYA

A THESIS SUBMITTED TO CHIANG MAI UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN BIOLOGY

GRADUATE SCHOOL, CHIANG MAI UNIVERSITY JULY 2017

a

DEVELOPMENT OF NEW TECHNIQUES OF SEED STORAGE AND DIRECT SEEDING OF NATIVE TREE SPECIES FOR TROPICAL FOREST RESTORATION

PANYA WAIBOONYA

THIS THESIS HAS BEEN APPROVED TO BE A PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
IN BIOLOGY

Examination Committee:

………………………….Chairman

(Assc. Prof. Dr. Kriangsak Sri-ngernyuang)

………………………….Member

(Dr. Stephen Elliott)

………………………….Member

(Asst. Prof. Dr. Prasit Wangpakapattanawong)

………………………….Member

(Dr. Dia Panitnard Shannon)

………………………….Member

(Dr. Pimonrat Tiansawat)

Advisory Committee:

………………………….Advisor

(Dr. Stephen Elliott)

………………………….Co-advisor

(Asst. Prof. Dr. Prasit Wangpakapattanawong)

………………………….Co-advisor

(Dr. Dia Panitnard Shannon)

26 July 2017

ACKNOWLEDGEMENTS

CONTENTS

CONTENTS (continued)

CONTENTS (continued)

LIST OF TABLES

LIST OF TABLES (continued)

Page

1

LIST OF TABLES (continued)

m

LIST OF FIGURES

Page

LIST OF FIGURES (continued)

Page

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

Page

LIST OF FIGURES (continued)

r

LIST OF FIGURES (continued)

Page

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

Page

LIST OF FIGURES (continued)

Page

ข้อความแห่งการริเริ่ม

1. ดุษฎีนิพนธ์นี้ได้นำเสนอขอมูลแห่งการริเริ่มของการใช้วิธีการหยอดเมล็ดและการเก็บรักษา
   เมล็ดเพื่อนำไปสู่การฟื้นฟูป่าโดยวิธีทางอากาศโดยการใช้เครื่องบินหรือการใช้อากาศยานไร้
   คนขับ ทั้งนี้เทคโนโลยีสมัยใหม่มีความจำเป็นอย่างยิ่งสำหรับการขยายพื้นที่การฟื้นฟูป่าตาม
   เป้าหมายสำคัญของโลก อาทิ โครงการ Bonn Challenge และการประกาศปฏิญญาแห่งเมือง
   นิวยอร์กด้านป่าไม้ (New York Declaration on forest)

2. ชนิดพันธุ์ไม้ที่ใช้ในการทดลองส่วนใหญ่ยังไม่ได้รับการทดสอบกับวิธีการหยอดเมล็ดและ
   การเก็บรักษาเมล็ดมาก่อน

3. ในการศึกษาครั้งนี้ได้มีการทดสอบประสิทธิภาพของสารปรับปรุงดิน หรือไฮโดรเจลเพื่อเพิ่ม
   ประสิทธิภาพให้กับวิธีการหยอดเมล็ดของไม้พื้นเมือง ซึ่งโดยทั่วไปจะใช้วิธีการดังกล่าวเพื่อ
   การเกษตรกรรม

4. ในการศึกษาครั้งนี้ได้มีการทดสอบผลของปุ๋ยละลายช้าที่ได้รับการพัฒนาใหม่จากศูนย์นาโน
   เทคโนโลยีแห่งชาติ สำนักงานพัฒนาวิทยาศาสตร์และเทคโนโลยีแห่งชาติ ซึ่งยังไม่มีการ
   นำมาใช้ทดสอบกับกล้าไม้พื้นเมืองมาก่อน

STATEMENTS OF ORIGINALITY

1. This project presents original data on direct seeding and seed storage, aimed at paving the way for aerial seeding by conventional aircraft or drones, new technologies that are essential to upscale forest restoration to meet recent ambitious global reforestation targets, set by the Bonn Challenge and the New York Declaration etc.

2. Most of the tree species covered had never been tested before for direct seeding and/or seed storage.

3. Furthermore, this study also tested the efficacy of using hydrogel to increase direct seeding success; a technology that, until now, has mostly been applied to agriculture and horticulture.

4. Lastly, this study tested the effects of a brand-new type of pelleted fertilizer produced by the National Nanotechnology Center (NANOTEC), the National Science and Technology Development Agency (NSTDA), that has never been tested before in the context of growing native forest tree species.

หัวข้อดุษฎีนิพนธ์	การพัฒนาเทคนิคใหม่ของการเก็บรักษาเมล็ดและการหยอดเมล็ด
	สปีชีส์ต้นไม้พื้นเมืองเพื่อการฟื้นฟูป่าเขตร้อน
ผู้เขียน	นายปัญญา ไวยบุญญา
ปริญญา	ปรัชญาดุษฎีบัณฑิต (ชีววิทยา)
คณะกรรมการที่ปรึกษา	ดร. สตีเฟน เอลเลียต อาจารย์ที่ปรึกษาหลัก
	ผศ. ดร. ประสิทธิ์ วังภคพัฒนวงศ์ อาจารย์ที่ปรึกษาร่วม
	ดร. เดีย พนิตนาถ แชนนอน อาจารย์ที่ปรึกษาร่วม

บทคัดย่อ

การหยอดเมล็ด หรือการนำเมล็ดปลูกลงพื้นที่ปลูกโดยตรง เป็นวิธีการที่ประหยัดในการนำมาใช้ฟื้นฟู
ป่า สามารถนำไปพัฒนาใช้กับการฟื้นฟูป่าโดยวิธีทางอากาศและสามารถใช้เป็นทางเลือกแทนการ
ปลูกป่าแบบดั้งเดิม ในการศึกษาครั้งนี้มีวัตถุประสงค์เพื่อ 1) หาสภาวะที่เหมาะสมต่อการเก็บรักษา
เมล็ดและศึกษาประเภทการเก็บรักษาเมล็ด 2) เปรียบเทียบวิธีการหยอดเมล็ดระหว่างสองช่วงเวลาคือ
หยอดเมล็ดทันทีหลังจากเก็บเมล็ดกับหยอดเมล็ดหลังจากเก็บรักษาในช่วงเวลาที่เหมาะสม 3)
เปรียบเทียบวิธีการหยอดเมล็ดกับวิธีการปลูกแบบดั้งเดิม และ 4) พัฒนาวิธีการหยอดเมล็ดให้ได้ผลที่ดี
ทำการทดลองกับไม้พื้นเมืองในเขตภาคเหนือ โดยการหาสภาวะที่เหมาะสมต่อการเก็บรักษาจาก
ทดลองการแปรผันสภาวะการเก็บรักษาที่อุณหภูมิและความชื้นของเมล็ดต่างกัน การเปรียบเทียบ
ช่วงเวลาการหยอดโดยนำเมล็ดไปหยอดในแปลงทดลองทันทีที่เก็บเมล็ดได้กับการเก็บรักษาเมล็ดช่วง
ระยะเวลาหนึ่งก่อนเพื่อรอหยอดในช่วงต้นฤดูฝนซึ่งเป็นช่วงเวลาที่เหมาะสม การเปรียบเทียบต้นกล้า
ที่มาจากวิธีการหยอดเมล็ดและต้นกล้าจากเรือนเพาะชำ นอกจากนี้ยังได้พัฒนาวิธีการหยอดเมล็ดโดย
การใช้ไฮโดรเจล ทั้งนี้ได้มีการเปรียบเทียบการงอก การอยู่รอด การตั้งตัว และการเจริญเติบโตของต้น
กล้า จากผลการทดลองแสดงให้เห็นว่า ร้อยละการงอก ค่ากลางการพักตัว และการเจริญเติบโต มีค่าไม่
แตกต่างกันอย่างมีนัยสำคัญทางสถิติระหว่างเมล็ดที่หยอดทันทีกับเมล็ดที่รอหยอดในช่วงต้นฤดูฝน
ส่วนไฮโดรเจลไม่มีผลต่อการงอก การอยู่รอด และการเจริญเติบโตของต้นกล้าเมล็ดประเภท
ออร์โทดอกซ์ สามารถเก็บรักษาเพื่อรอหยอดเมล็ดพร้อมกันในช่วงต้นฤดูฝนได้ ในขณะที่เมล็ด

d

ประเภทรีคาลซิแทรนท์ควรหยอดเมล็ดทันทีเพื่อยังคงให้เมล็ดมีชีวิตอยู่ จากผลการทดลองสามารถนำไปประยุกต์ใช้กับการฟื้นฟูป่าโดยวิธีทางอากาศต่อไป

Dissertation Title	Development of New Techniques of Seed Storage and Direct Seeding of Native Tree Species for Tropical Forest Restoration
Author	Mr. Panya Waiboonya
Degree	Doctor of Philosophy (Biology)

Advisory Committee	Dr. Stephen Elliott	Advisor
	Asst. Prof. Dr. Prasit Wangpakapattanawong	Co-advisor
	Dr. Dia Panitnard Shannon	Co-advisor

ABSTRACT

Direct seeding (sowing seeds directly into ground) is a low cost method of forest restoration, which could potentially be applied to aerial seeding and replace conventional tree planting. The study presented here aimed to: i) determine optimal seed storage conditions and behavior of native forest tree species, ii) compare direct seeding success between seeds sown at the time of seed collection and those stored from collection time to optimal seeding time, iii) compare direct seeding with conventional tree planting and iv) develop treatments to increase direct seeding success. Seeds were stored under various temperatures and moisture contents, to determine storage behaviour and identify optimal storage conditions. Seeds were sown into a deforested site, immediately after collection and after storage at the beginning of rainy season. Seeds were also sown with various proportions of hydrogel, to determine if it could increase germination. Growth performance was compared among seedlings under the different sowing conditions and with seedlings grown in a nursery. In general, germination and median length of dormancy (MLD) did not differ significantly between seeds sown at collection times and those stored and sown at the beginning of rainy season. Furthermore, differences in seedling growth rates among the treatments were insignificant. Hydrogel also had no significant effects on seed germination, mortality and MLD. Most species could be sown, with good results, shortly after the seed collection date and recalcitrant seeds must be

sown at that time. Alternatively orthodox species could be stored and sown all together at the start of the rainy season, for increased cost-effectiveness.

CHAPTER 1

Introduction

1.1 Historical Background

Tropical forests have been severely degraded, mainly due to anthropogenic disturbances. This critical reduction in forest cover is a major driver of biodiversity loss and is having a substantial impact on the global climate. Therefore, degraded forest land should be restored back to forests, as quickly as possible, to bring back ecosystem services and functions (Lamb et al., 2005).

Forest restoration practices vary greatly, depending on the initial degree of degradation, the type of the target forest to be restored, climatic conditions and surrounding landscape factors. However, restoration is possible, even under the harshest of conditions, such as those on mine sites (e.g. Fields-Johnson et al., 2012). Techniques vary from relying on natural regeneration, assisting (or accelerating natural regeneration (ANR) to planting the maximum number of tree species (Miyawaki, 1993) or planting seedlings of a few (20-30 species) functionally significant native tree species to foster natural regeneration: the so-called "framework species method" of Goosem and Tucker (1995). The latter involves selecting species with high field performance, ability to shade out weeds and provision of resources to attract seed-dispersing animals at the early stage. The framework species method was originally conceived in Queensland, Australia, for lowland rain forests and has been successfully modified to restore seasonally dry tropical forest in northern Thailand by Forest Restoration Research Unit, Department of Biology, Chiang Mai University (FORRU-CMU) (Elliott et al., 2013). The method has been successful at attracting seed-dispersing birds into restored areas (Wydhayagarn et al., 2009), which promote rapid diversification of the understory.

1

Forest restoration mostly involves planting trees in degraded land. Propagating trees in nurseries is costly in terms of labour, time, equipment, irrigation systems etc. Hence, establishing forest from seeds should reduce costs and allow sites, without a nearby nursery, to be restored. Although, direct seeding could potentially improve the cost-effectiveness of forest restoration, it does not work for all desired species. Seed size plays a vital role in seedling establishment success, with larger seeds having higher establishment rates than smaller ones (Doust et al., 2006; Doust et al., 2008; Tunjai and Elliott, 2012). However, small seed-sized species can be established, if diseases are prevented at the establishment stage (Kuaraksa and Elliott, 2013).

Seed predation can prevent seedling establishment. Ants are a major cause of predation in abandoned agricultural land in northern Thailand (Woods and Elliott, 2004). Rodents are also major seed predators e.g. of *Quercus* species (Birkedal et al., 2009). Hence, burying seeds usually reduces seed losses due to predation (Woods and Elliott, 2004) and increases establishment rate (Doust et al., 2006; Doust et al., 2008). In field trials, which compared performance of direct seeded trees with nursery-raised ones, the former grew faster than the latter over one year after planting (Tunjai, 2005). However, so far, few framework trees species have been tested like this and further experiments are needed to identify a wider range of species that perform well from direct seeding.

In Thailand, direct seeding has only been carried out using species, that produce seeds just before the optimum direct seeding time (which is 4-6 weeks into the rainy season i.e. mid-June in northern Thailand, FORRU, 2006). Direct seeding could have wider applications if seeds, produced at other times of the year could be stored until the optimum direct seeding time, or if the method could be implemented at other times of the year with good results. Most studies have avoided or ignored the risk of seed storage on the overall outcome of direct seeding (Doust et al., 2006; Doust et al., 2008; Tunjai and Elliott, 2012). Only a few studies investigated the effects of different seed sowing times on seedling establishment (beginning and late rainy season of sowing) and no similar study has been performed in seasonally dry tropical forest ecosystems, where seasonal variation in weed growth is much more marked.

2

Most tropical forest seeds cannot be stored for long periods, without considerable loss of viability (Doust et al., 2006; Doust et al., 2008; Tunjai and Elliott, 2012). The seed storage behavior of framework species should be studied, since it could be applied to aerial seeding, storing seeds as genetic resources, or providing a seed supply when trees fail to fruit. Hence, it is important to know how long seeds can be stored and under which conditions.

1.2 Research Objectives

1. To determine optimal seed storage conditions of native tree species, from fruiting times to optimal direct seeding time.
2. To compare direct seeding success between seeds sown at the time of seed collection and those stored until the optimum direct seeding season.
3. To compare direct seeding with conventional tree planting.
4. To develop treatments to improve direct seeding success.

1.3 Usefulness of the Research

1. This study will help to develop novel and effective techniques to restore tropical forest ecosystems. It will help to meet the increasing demand for technical knowledge of forest restoration since REDD+ included "enhancement of carbon stock" as a valid mitigation mechanisms for global climate change.

2. The framework species approach meets the stipulation that forest restoration must include biodiversity recovery and meet the needs of local people for a diverse range of forest products, since the method places strong emphasis on diversity.

3. To improve direct seeding by enabling wider species choices and developing protocols that will make forest restoration more feasible over large areas and thus enable forest restoration to contribute significantly towards climate change mitigation.

4. Understanding seed storage can be applied to developing aerial seeding methods and maintaining genetic diversity, through access to stored seeds. It will also make forest restoration possible even where seeds are unavailable from nearby forests.

CHAPTER 2

Literature Review

2.1 Global View

2.1.1 Deforestation: Causes and Consequences

Forests play vital roles in human livelihoods. They provide many goods and services through i) supporting soil formation, photosynthesis and nutrient cycles ii) regulating air quality, climate, water purification and soil erosion iii) provisioning of food, medicine, fresh water and raw materials and iv) cultural services in spiritual and religious values, recreation and ecotourism and mental and physical health (WWF, 2016). They are also crucial in carbon storage. Globally, about 645 Pg C[1] is stored in the vegetation and about 1,567 Pg C in the soil across all biomes (Prentice et al., 2001). The net rate of carbon accumulation in all forest biomes is about 1–3 Pg C/year, of which 0.4 Pg C/year is added to forest soils (Lal, 2005). Unfortunately, world forest cover has dramatically declined especially in the tropics. In 2015, forests covered 3,999 million hectares or 30.6 percent of Earth's total land area. Although, the annual global rate of net forest loss declined slowly from 1990s, it remains high at about 3.3 million hectares per year (2010-2015, (FAO, 2015).

In the tropics, forest degradation is driven by various factors; agriculture (commercial and subsistence), surface mining and urban expansion (Hosonuma et al., 2012). Agriculture (small and large scale) is the main driver, which caused more than 80% of deforestation across the Africa America and Asia continents (Figure 2.1). In tropical countries, large-scale commercial and local subsistence agriculture accounted for 40% and 33% of deforestation respectively (FAO, 2016).

---

[1] Petagram (Pg) of Carbon – One Pg $=10^{15}$ grams = one billion metric tonnes

In addition, tropical countries exhibited net forest loss of 7 million hectares per year, whereas agricultural land were increased of 6 million hectares per year from 2000-2010 (Figure 2.2, FAO, 2016). In Southeast Asia for example, forest cover was estimated at 268 million hectares in 1990 and dramatically decreased to 236 million hectares by 2010. Land conversion to cash crop plantation and selective logging were the main drivers (Stibig et al., 2014).
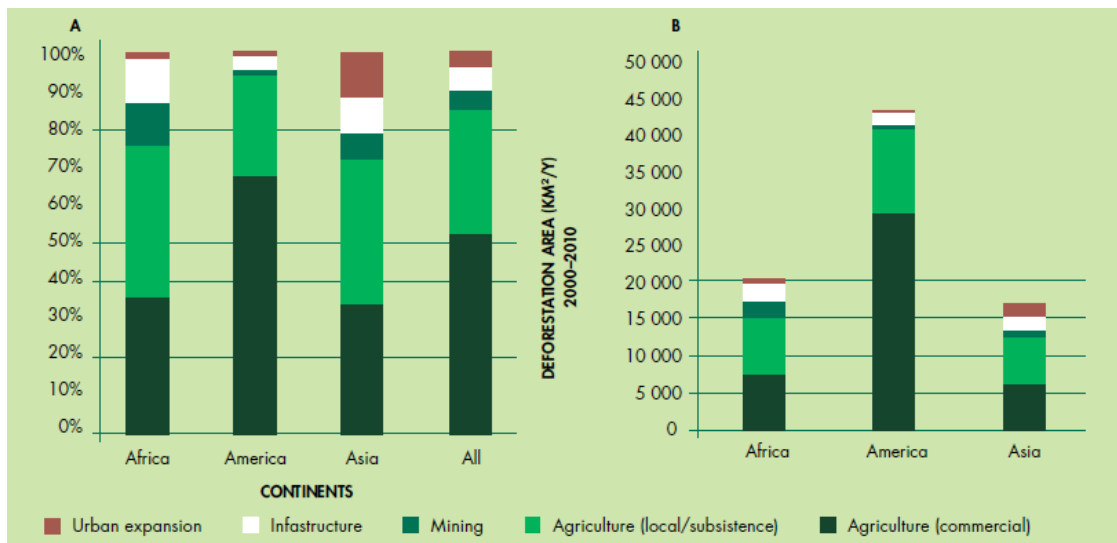
Figure 2.1 Estimate of (A) proportion of total area of land-use change associated with various proximate drivers of deforestation, and (B) Absolute net forest area change associated with proximate drivers of deforestation, by region, 2000-2010 (FAO, 2016)
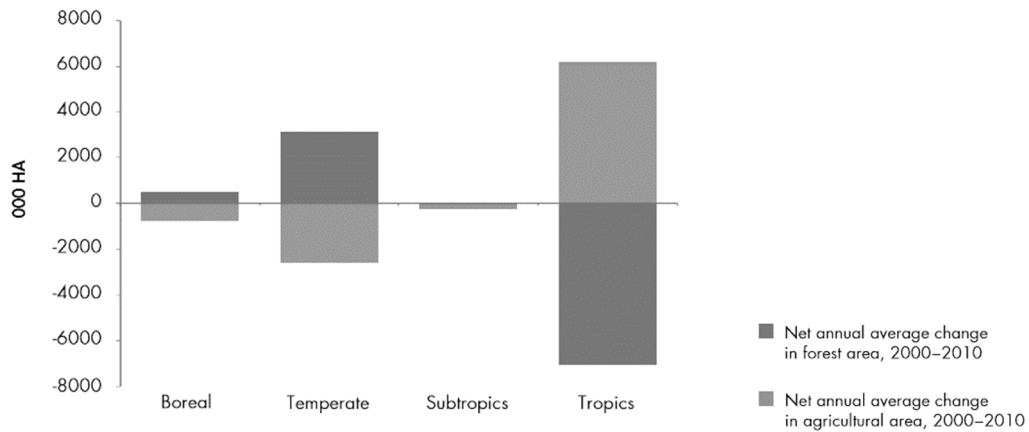
Figure 2.2 Net annual average change in forest and agricultural land by climatic domain 2000-2010 (FAO, 2016).

Deforestation and forest degradation lead to habitat loss and consequently biodiversity decline. From 1970-2012, the living planet index (LPI) of vertebrates declined by 58 % of overall population abundance (WWF, 2016). More than 5,520 mammal, bird, amphibian and insect species are threatened with extinction due to habitat loss and degradation, overexploitation, pollution, invasive species, diseases and global warming (WWF, 2016). In Indonesia, for example, a biodiversity hotspot, forests have declined by 47,600 hectares per year, amounting to 6.02 million hectares lost over 12 years (2000 to 2012) (Margono et al., 2014).

Concentrations of atmospheric greenhouse gasses are increasing. Carbon dioxide concentrations have increased by 40% since pre-industrial times (IPCC, 2013), of which deforestation and forest degradation have contributed about one third of the global anthropogenic carbon emission (Denman et al., 2007). Emissions from tropical countries (including the draining and burning of peat swamps in South East Asia) over the twenty years of 1990-2010 averaged 1.4 Pg C/year (Houghton, 2012). This has caused global temperature to rise by 0.85 °C from 1880–2012. The Ocean is warmer than in past century by 0.11 (0.09-0.13) °C. Sea level rose by an average of 0.19 m from 1901 to 2010, due to thermal expansion of the oceans, combined with the melting of polar ice caps and glaciers (IPCC, 2013).

Global temperature seems set to increase much more, substantially changing ecosystem components, so mitigation actions need to be substantial, to bring about a sustained reduction of greenhouse gas emissions (IPCC, 2013). Forests are net carbon sinks where carbon is sequestered in biomass (particularly tree trunks and roots) both above and below ground and as dead organic matter in the soil.

2.1.2 Reforestation

The United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD) was launched in 2008. It drew upon the technical expertise of the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP) and the United Nations Environment Programme (UNEP). The UN-REDD Programme has 3 main tasks: i) design and implement REDD+ programmes at national levels, ii) support national REDD+ action plans and iii) support technical capacity building. The goal of the programme is to "*reduce forest emissions and enhance carbon stocks in forest, while contributing to national sustainable development*".

In 2011, the Bonn Challenge committed from governments, organizations, communities and individuals to share in the common goal of "*restoring the world's degraded and deforested lands*". The Challenge targeted the restoration of 150 million hectares of degraded forest by 2020. It appears that this goal is being achieved faster than expected, according to world leaders who gathered at the UN Climate Summit in New York in 2014. They agreed on an even more ambitious target for global reforestation in the New York Declaration on Forests "… *at least halve the rate of loss of natural forests globally by 2020 and strive to end natural forest loss by 2030. Support and help meet the private-sector goal of eliminating deforestation from the production of agricultural commodities such as palm oil, soy, paper and beef products by no later than 2020, recognizing that many companies have even more ambitious targets. Significantly reduce deforestation derived from other economic sectors by 2020. Support alternatives to deforestation driven by basic needs (such as subsistence farming and reliance on fuel wood for energy) in ways that alleviate poverty and promote sustainable and equitable development. Restore 150 million hectares of degraded landscapes and forestlands by 2020 and significantly increase the rate of global restoration thereafter, which would restore at least an*

additional 200 million hectares by 2030..." (UN Climate Summit, 2014). Organizers of the challenge claim that 148.38 million hectares have already been restored, sequestering 15.1 Gigaton of Carbon dioxide and injecting 46,595 million US Dollars into the economies of the participating countries (Bonn Challenge, 2017).

2.1.3 National Examples

Brazil serves as a good example. It is rich in biodiversity, being classified as one of the world's megadiverse countries (CBD, 2017a). However, deforestation rates are very high, 0.2% or 984,000 hectares per year, ranking it among the top ten countries in terms of annual forest loss, 2010-2015 (FAO, 2015). Fragments of Atlantic forest along the country's eastern coastline are small (more than 80% are less than 50 ha) and widely separated (averaging 1440 m apart, Ribeiro et al., 2009). The Atlantic Forest Restoration Pact (AFRP). AFRT is collaborative programme, with more than 260 stakeholders from the government, private sector, NGOs and researchers. It aims to restore 15 million ha of degraded and deforested lands by 2050 (Pinto et al., 2014). The AFRT is part of The Bonn Challenge, committed 12 million ha goal by 2030 (Bonn Challenge, 2017). In addition, the AFRT is attempting to add economic value, less expensive and profitable, to the restoration project (Pinto et al., 2014).

China launched a similar large-scale programme called Grain for Green Programme (GGP) in 1999, to restore forest to the central and western parts of the country, principally to control soil erosion. The GGP has already restored over 20 million ha of forest on formerly agricultural land, with a budget of USD 40 billion. This programme has increased soil organic carbon accumulation at different soil depths (Song et al., 2014) and has sequestered a total of 12.3 tC ha-1 in above- and below-ground biomass over 10 years, equivalent to 14% of China's total carbon emissions in 2009 (Persson et al., 2013).

2.2 Forest Status in Thailand

Thailand covers an area of 513,115 km^2 in South East Asia. The country has several unique ecosystems, both terrestrial and aquatic, which support very a high biodiversity. For example, more than 10,000 species of vascular plants, belonging to 275 families of spermatophytes and 36 families of pteridophytes, have been recorded (DNP, 2017). Vertebrate species number at least 4,722 (Table 2.1) and invertebrates, 124,526 representing 5% and 12% of world species record, respectively (ONREP, 2014). Seven vertebrate species have gone extinct and 555, or 11.75%, are "threatened" (Table 2.1). In particular, several megafauna species are very rare, e.g. only 50-70 wild water buffalo remain and 200-500 tigers, whilst both the Javan and Sumatran rhinos have been extirpated (CBD, 2017b).

Table 2.1 Number of vertebrate species found in Thailand and threaten status (ONREP, 2014)

Classification	Species found in Thailand	Threatened species	
		Numbers (kinds)	percentage
Mammals	336	118	35.12
Birds	1,010	168	16.63
Reptiles	394	49	12.44
Amphibians	157	18	11.46
Fishes	2,825	202	7.15
Total	4,722	555	11.75

The country's rich biodiversity has been decreasing as economic growth and population growth have been increasing. Forest lands, wildlife habitat, were converted to agricultural land and other land uses to support economic development, with an average loss of 162,200 km^2 per year, from 2008 to 2014 (ONREP, 2014). The first forest survey in 1961, carried out by aerial photography, found that just over half the country remained forested (53.33%), but by 1989, just over half of the original forest remained (27.95% cover) due to intensive logging and land conversion. Faced with huge loss of biodiversity and forest land, the Thai government canceled all forest concessions in that year.

The Thai government established a policy to maintain 40% of the country under forest in 1985, including 25% economic forests and 15% protected forests. Following the logging ban, less land was required for economic forests, so in 1992, the government swapped these goals to 25% protected forest and 15% economic forests in the Seventh National Economics and Social Development Plan B.E. 2535-2539 (NESDB, 1992).

Surprisingly, forest cover suddenly increased in 1998 from 25.28% to 33.15 in 2000 (Figure 2.3). This may have been an artifact of increasing satellite imaging resolution used for forest assessments from 1:250,000 to 1:50,000 scale. Consequently, more tiny forest patches could be included into the country report (Seub Foundation, 2016). Consequently it appears that forest cover has increased, since forest concessions were cancelled, reaching 31.60% in 2015 (Figure 2.3). Many former logging concession areas were merged with the 238 protected areas that now cover 19% of the country (DNP, 2017).
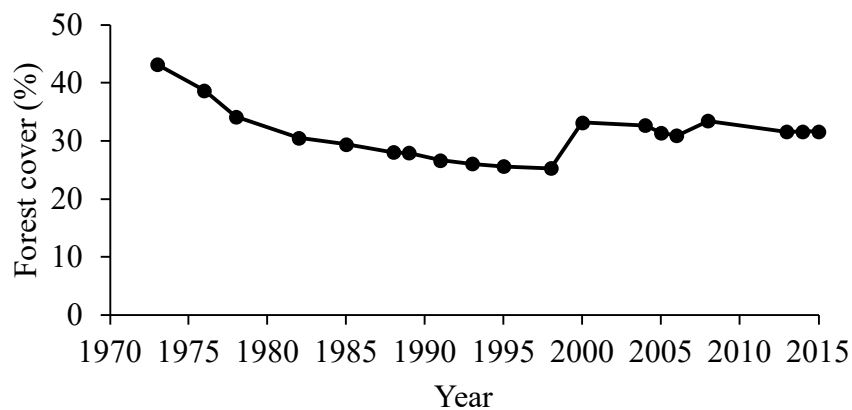
Figure 2.3 Forest cover in Thailand during 1973-2015 (modified from RFD, 2015).

2.3 Forest Restoration

The Society for Ecological Restoration (SER, 2002) defines ecosystem restoration generally as "the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed". FAO stated that the main purpose of forest restoration is "to re-establish the presumed structure, productivity and species diversity of the forest originally present at a site" (Sustainable Forest Management Toolbox (SFM), FAO, 2017). All these definitions share the goal of restoring degraded land to its original pre-degradation state. The definition of tropical forest ecosystem restoration used as the basis of this study is "Directing and accelerating ecological succession towards an indigenous target forest ecosystem of the maximum biomass, structural complexity, biodiversity and ecological functioning that can be self-sustained within prevailing climatic and soil limitations." (modified from Elliott et al., 2013)

Understanding the initial level of site degradation is key to success. It enables strategies or techniques to be selected, which are suited to the conditions prevalent at any particular degraded site. There are five levels of degradation that determine restoration approach. They are determined by 3 site (restoring site) and 3 landscape (surrounding area) degradation thresholds. For site-critical thresholds, it is necessary to consider the density of natural regenerants[2], weed competition and soil degradation. Whilst, landscape-critical thresholds include proximity of climax forest, abundance of seed dispersers and fire risk. For instance, stage-1 degradation follows selective logging where tree cover remains dense enough to suppress herbaceous weeds, natural regenerants are common and soils mostly remain fertile. Large remnants of climax forest are nearby, seed-dispersing animals remain common and fire risk is low to medium. The recommended restoration strategy for such areas is protection; prevention of encroachment, cattle, fire and hunting of seed dispersers. In contrast, stage-5 degradation refers to sites that are highly disturbed, have no tree cover, few or no natural regenerants and eroded soils. Remnant climax forest patches are remote and seed dispersing animals have mostly been hunted out. Fire risk is low initially (due to low fuel loads), but increases as weeds recolonize. In such areas, soil

---

[2] *i.e.* seedlings, saplings, trees and live tree stumps, capable of coppicing

quality must first be improved before planting of nurse tree species and subsequent re-introduction of more diverse species of tree seedlings (Table 2.2, Elliott et al., 2013).

Table 2.2 Simplified guide to choosing a restoration strategy (from Elliott et al., 2013)

Landscape-critical thresholds			Site-critical thresholds			Suggested restoration strategy
Forest in landscape	Seed-dispersal mechanism	Fire risk	Vegetation cover	Natural regenerants	Soil	
Remnant forest remains within a few km of the restoration site	Mostly intact, limiting the recovery of tree species richness	Low to medium	Tree canopy cover exceeds herbaceous weed cover	Natural regenerants exceeds 3,100/ha with more than 30** common tree species represented	Soil does not limit tree seedling establishment	Protection
		Medium to high	Tree crown cover insufficient to shade out herbaceous weeds			Protection + ANR*
		High	Herbaceous weed cover greatly exceeds tree crown cover	Natural regenerants sparser than 3,100/ha with fewer than 30** common tree species represented		Protection + ANR + Planting Framework tree species
Remnant forest patches very sparse or absent from the surrounding landscape	Seed-dispersing animals rare or absent such that the recruitment of tree species to the restoration site will be limited				Soil degradation limits tree seedling establishment	Protection + ANR + Maximum diversity tree planting
		Initially low (soil conditions limit plant growth); higher as the vegetation recovers	Herbaceous weed cover limited by poor soil conditions			Soil amelioration + Nurse tree plantation, followed by thinning and gradual replacement of maximum diversity tree planting

* ANR Accelerate Natural Regeneration

** Or roughly 10% of the estimated number of tree species in the target forest, if known

Species selection plays the vital role in ecosystem restoration. Native species have been widely used for ecological restoration to complement natural regeneration (Miyawaki, 1998; Miyawaki, 2004; Elliott et al., 2013). The diversity of tree species planted depends on degradation stage (Table 2.2). Restoration may require planting only a few native trees or the maximum number of species possible. The Miyawaki method is one of the most successful restoration techniques for severely degraded sites with low or absent incoming seed dispersal. The method involves vegetation and soil surveys and the planting of as

diverse a range of native tree species for planting species as possible at very high densities. Mulching is initially applied after planting, to maintain soil moisture, suppress weed growth and prevent soil erosion. Weeding is essential over the first 3 years, cut weeds serve as additional mulching (Figure 2.4) This method was first applied in Japan in the 1970s and was introduced globally to South-East Asia, China and South America (Miyawaki, 2004).
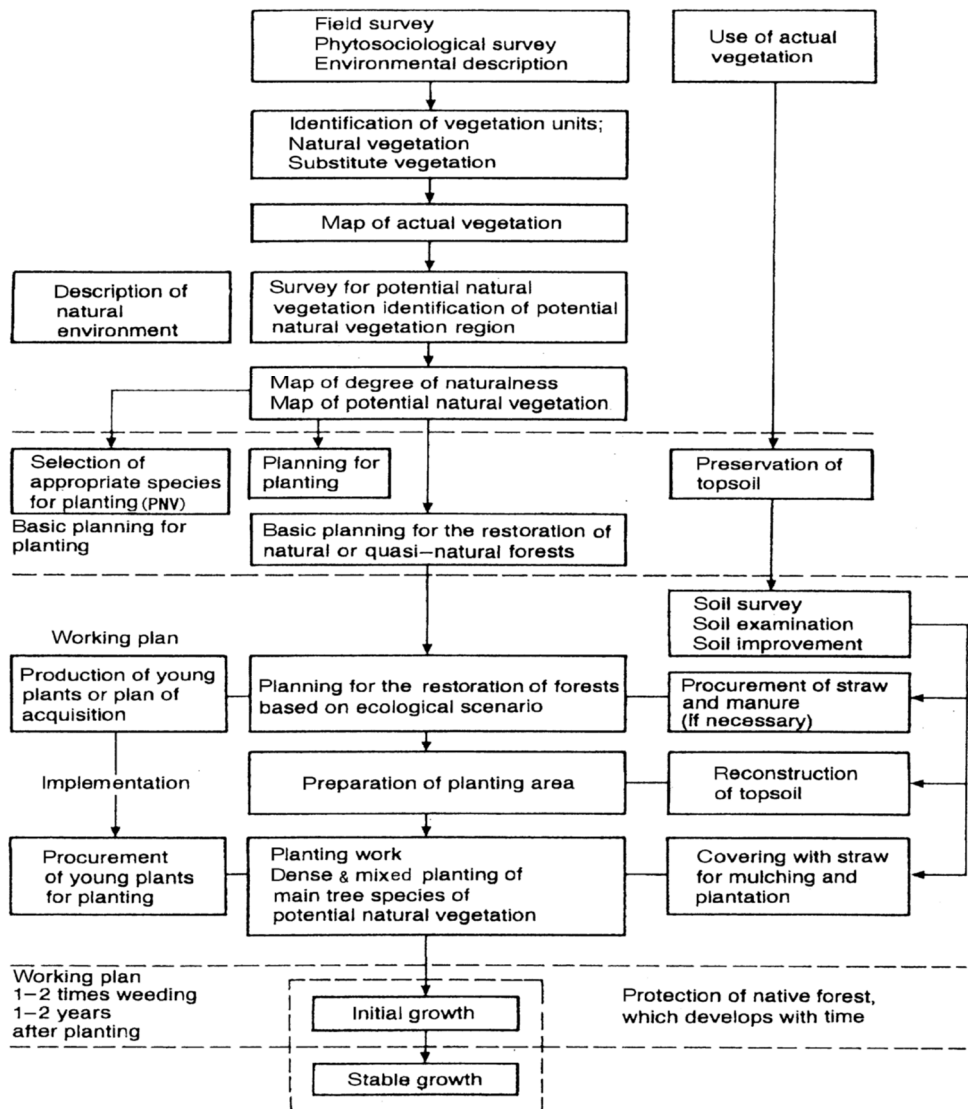
Figure 2.4 The Miyawaki method summarized as a flow chart (Miyawaki, 2004)

In the Mediterranean environment, the Miyawaki method successfully restored Italian forest with higher biodiversity compared with conventional techniques (planting *Pinus pinaster* Aiton (maritime pine), *Pinus halepensis* Miller (Aleppo pine), *Cedrus atlantica* (Endl.) Carrie`re (Atlas cedar), *Quercus suber* L. (cork oak), *Quercus pubescens* Willd. (downy oak), and *Castanea sativa* Miller (sweet chestnut), new plant community was able to re-establish without support (Schirone et al., 2011). In Shanghai, China, the Miyawaki concept was applied to urban ecosystem reconstruction by restoring climax to the city and coining the new term: Near-Natural Method of Afforestation (Da, and Guo 2014). Although the method showed promised restoring results, labour and planting costs were very high due to the high plant diversity required (Schirone et al., 2011).

Accelerated or Assisted Natural Regeneration (ANR) is cost-effective and requires low labour input (Table 2.3). The lack of need for a nursery considerably reduces the cost of this technique (Shono et al., 2007). The technique involves reducing the barriers to natural regeneration including: low site resources (soil quality), ongoing disturbances (fire, cattle grazing), competition with weeds and low regenerant density (Hardwick et al., 2004). ANR could be integrated broadly into various restoration regimes for various purposes from biodiversity recovery to economic plantations (Shono et al., 2007). However, this technique is limited where the level of degradation is high (Table 2.2).

Table 2.3 Various reforestation approaches and their merits (Shono et al., 2007)

Reforestation Approach	Costs (Labour and Capital)	Biodiversity	Time for Forest Development	Research Input Required
Commercial monoculture plantation	High[a]	Low	Fast	Low
Monoculture of commercial nurse trees	High[b]	Low to medium	Fast[c]	Low
ANR without enrichment planting	Low	Low to medium	Slow to medium	Low
ANR with enrichment planting	Low to medium	Medium	Medium	Low to medium
Framework species method	Medium to high	Medium	Medium	High
High-density planting of forest trees	High	High	Fast	High

[a] The high establishment and operational costs are generally recovered by profits.
[b] Some of the establishment cost may be recovered by harvesting of nurse trees.
[c] Nurse trees grow fast, but understory develops slowly.

2.4 The Framework Species Method

Forest restoration has been studied worldwide and practical methods have been developed to increase its effectiveness. The framework species method has rapidly become accepted as an effective and practicable way to restore tropical forests, largely due to the work of Goosem and Tucker (1995) and Chiang Mai University's Forest Restoration Research Unit (FORRU-CMU) (Elliott et al., 2013). It was conceived to restore tropical forest in Queensland, Australia (Goosem and Tucker, 1995) and involves planting saplings of 20-30 native forest tree species, including both pioneers and climax species (Figure 2.5). Framework species are defined by the following criteria; high field performance (i.e. high rates of survival and growth), ability to shade out herbaceous weeds with dense broad crowns and the provision of resources, which attract seed-dispersing animals at a young age. The method has been applied to seasonally dry tropical forest in northern Thailand and researched extensively by FORRU-CMU. The unit has published many books and papers on tropical forest restoration, based on field and nursery research results (FORRU, 2006; FORRU, 2008; Elliott et al., 2013).

This method rapidly recovers biodiversity and restores forest ecosystems to degraded land. It promotes recruitment of non-planted tree species into restoration plots, mostly via seed dispersal by birds (Wydhayagarn et al., 2009). Best-performing framework tree species have been identified (Elliott et al., 2003) and optimal silvicultural treatments determined (FORRU, 2006). Canopy closure can now be achieved within 3 years after planting (with a planting density of 3,100 trees per hectare). Rapid biodiversity recovery was also achieved. Sinhaseni (2008) reported that 73 non-planted trees species re-colonized the plots within 8–9 years. When combined with the 57 planted framework tree species, the total tree species richness in the sampled plots amounted to 130 (85% of the tree flora of the target evergreen forest). The species richness of the bird community increased from about 30 before planting to 88 after 6 years, including 54% of the species found in the target forest (Toktang, 2005).
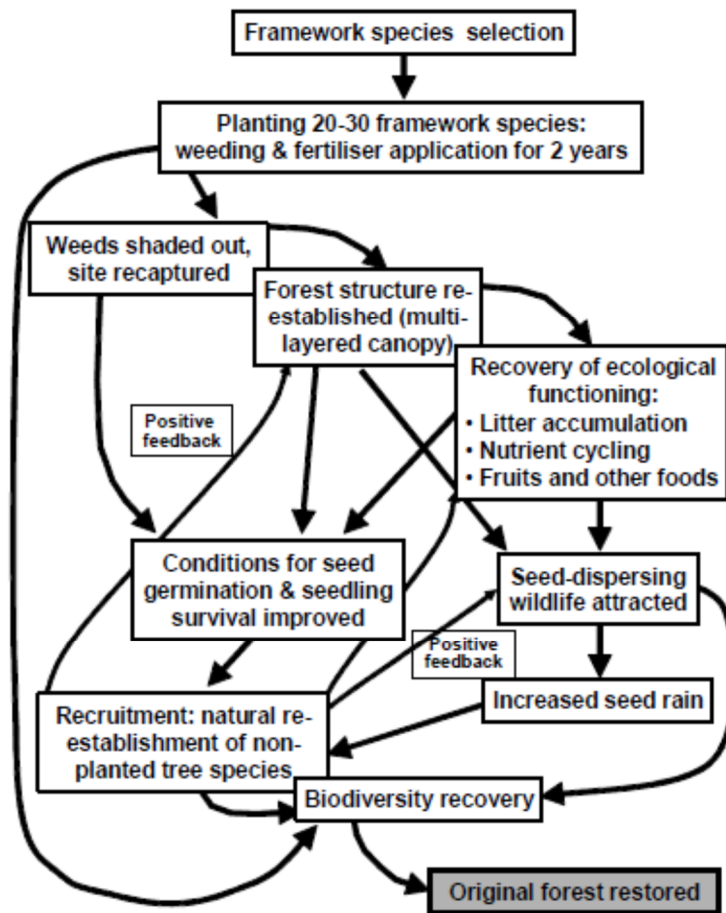
Figure 2.5 Concept of framework species method (FORRU, 2008)

2.5 Direct seeding

Direct seeding – as the name suggests – is replacing tree planting with sowing seeds directly into the soil of the restoration site. The method is low cost since nursery production of planting stock, a major cost of conventional restoration, is not required. Its successfulness depends on various factors, including seed traits, physical factors and controlling seed predation. Seed traits, including seed size or mass, shape and seed coat thickness, play vital roles in seedling establishment success. Large-seeded species usually have higher rates of germination (Figure 2.6) (Ceccon et al., 2015; Palma and Laurance, 2015) and seedling establishment (Doust et al., 2006; Doust et al., 2008; Tunjai and Elliott, 2012). Seedlings growing form small seeds fail to survive the early stages of development. For example, *Ficus* species seedlings have more than 90% mortality, mostly due to damping-off diseases within a month and those that do avoid disease are

all killed during the first dry season (Kuaraksa and Elliott, 2013). In southern Thailand lowland forest, large to intermediate-sized seeds, which were round or oval and had low to medium moisture content had higher seedling survival rates than species with other seed characteristics (Tunjai and Elliott, 2012).
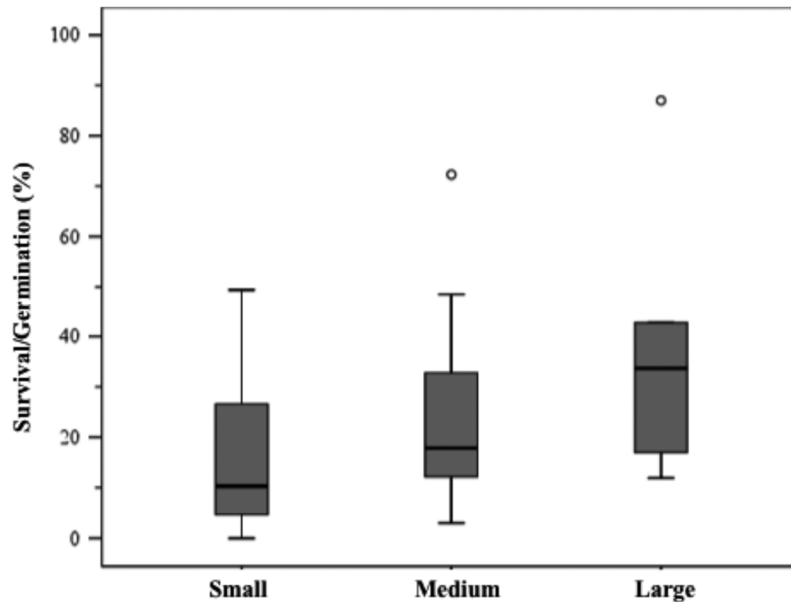
Figure 2.6 Survival/germination according to seed size (mass) in direct seeding experiments. Seed mass categories: Small: seeds 0–99 mg (n = 29); Medium: 100–2000 mg (n = 14); Large: >2000 mg (n = 6). ANOVA; F = 5.0 df = 2, P < 0.01. The tick line represents the median, the outer limits of the box the first and third quartiles. Whiskers extend to cover any data point <1.5 times the interquartile range. Circles represent outliers (Palma and Laurance, 2015).

Physical factors (light, moisture) have a great influence on direct seeding success. For example, when four canopy species were planted into primary dry forest in Jamaica, seedling survival rates were lower in non-shaded than in shaded plots (McLaren and McDonald, 2003). Regeneration guild (early or late successional status) may affect seedling establishment and seeds of tree species in different guilds may require different germination conditions (Engel and Parrotta, 2001; Cole et al., 2011). In addition, different times of sowing present different weed competition conditions (Doust et al., 2008).

Seed predation severely reduces seedling establishment. For example ants destroyed seeds in abandoned agricultural land in northern Thailand (Woods and Elliott, 2004) and cattle may also be a cause of seedling predation (FORRU, 2006). Rodents are the major seed predators in various type of restoration site (Hau, 1997; Hau, 1999; Birkedal et al., 2009; Castro et al., 2015). Rats, including *Niviventer fulvescens* and *Rattus rattus flavipectus*, were the main seeds predator in a shrub-land restoration project in Hong Kong. Seeds of 11 out of 12 species studied were removed from the restoration site within 60 days. However, rodents removed few *Choerospondias axillaris* and *Elaeocarpus sylvestris* seeds probably because they have thick or tough seed coats (Hau, 1997). Coating seeds or protecting them physically might help to reduce seed predation during direct seeding projects for forest restoration (Castro et al., 2015).

Further studies are needed to incorporate direct seeding into tropical forest restoration protocols around the world. Greater understanding is needed about the time frame of the method from seed collection preparation to the establishment of a closed canopy forest. The costs-effectiveness of direct seeding should be more widely compared with that of other restoration techniques and the likely effects of climate change on direct seeding success (both in terms of species selection, seed germination and seedling establishment) should be explored (Palma and Laurance, 2015). In addition, more tree species should be tested for direct seeding to improve our understanding in this method and identify situation when direct seeding alone is enough to restore forest ecosystems and when it should be complemented with ANR or conventional tree planting (Silva et al., 2015). Cost-effectiveness is one of the main benefits of using this technique. However, this is not true for all species. The high mortality of small-seeded species such as *Ficus* spp resulted in very high cost of per plant established compared with planting nursery-raised seedlings and planting stock from vegetation propagation (Kuaraksa and Elliott, 2013).

2.6 Seed Storage

In tropical forests, trees produce seeds in all months of the year. For example, in Doi Suthep-Pui National Park, 43% of wind-dispersed tree species mainly produce seeds during the mid to late dry season, whilst animal-dispersed species tend to produce seeds in late rainy season (FORRU, 2006). The optimum seed-sowing period is the beginning of the rainy season, so direct seeding may be limited to only those tree species that fruit just before that period. Such a limitation considerably reduces the ability of direct seeding to replicate high tree species richness at the start of a restoration project. Therefore, efficient seed storage, from fruiting time to the optimum direct seeding time, could play a major role in making direct seeding technique a more attractive restoration tool (Guarino and Scariot, 2014).

Seed storage and longevity behavior can be classified as orthodox, recalcitrant or intermediate (Hong and Ellis, 1996; Schmidt, 2007). It depends on the ability of seeds to tolerate desiccation, chilling and the duration of storage. The viability of orthodox seeds can be maintained *ex situ* for long periods. They tolerate both chilling and drying. Recalcitrant seeds are desiccation-sensitive. They cannot survive chilling and/or drying. Short-term storage can be possible, but only under specialized conditions. Intermediate species are half way between orthodox and recalcitrant. Chilling may prolong viability to some extent either wet or dry. Medium-term storage is possible, when storage conditions are well-defined and controlled. For direct seeding, intermediate species may be suitable if the time from seed collection to direct seeding is not too long. Thus, knowledge of storage behaviour is essential for defining suitable storage environments and knowing the likely longevity of tree seeds both for restoration and for species conservation projects (Hong and Ellis, 1996).

Storage behaviour can also be identified by probabilistic models, which are based upon the dry seed mass and the seed coat ratio, SCR, is the proportion of dry seed coat and dry seed mass. These parameters have been found to be reliable predictors of storage behaviour. Large seeds with relatively low SCR (thin seed coats) are usually desiccation-sensitive (Daws et al., 2006).

Seed storage behaviour has been studied worldwide in different plant families. In Sri Lanka, a hundred species of Fabaceae, both native and introduced species, were classified into 94 orthodox species and 6 non-orthodox (Jayasuriya et al., 2013). In Vietnam, Hong and Ellis' Protocol was tested on 51 native and 9 introduced tree species, of which 34 were orthodox, 13 intermediate and 13 recalcitrant (Ellis et al., 2007). A similar trend was found in Brazilian Amazon rainforest, where orthodox species were the most common. Sixty-seven tree species were tested, of which 38 were orthodox, 23 recalcitrant and 6 intermediate (De et al., 2014).

2.7 Hydrogels

Hydrogels or hydrophilic gels are hydrophilic crosslinked polymers. These polymers can be classified into three different groups, according to their synthetic process. Firstly, naturally occurring polymers are essential for life components, such as proteins, polysaccharides and other starch derivatives. These polymers are normally used in the food industry as thickening agents. Natural gums (including Arabic gums and guar gum) and agar are other examples of natural polymers. Secondly, semi-synthetic polymers are combinations of natural polymers (cellulose) and petrochemical derivatives, such as cellulose ethers. Thirdly, synthetic polymers or hydrogels are synthesized from monomers of petrochemicals, including cross-linked polyacrylamide (PAM) $(-CH_2CHCONH_2-)_n$, hydroxyethyl methacrylate and polyvinyl alcohol $(-CH_2CHOH-)_n$ (Mikkelsen, 1994). Hydrogels have been used for different purposes, such as biomedical products, biotechnologies, pharmaceuticals, separation technologies, electro-conduction and biosensors, contact lenses, food packaging, cosmetics, oil-spill recovery and agriculture (reviewed in Ullah et al., 2015).
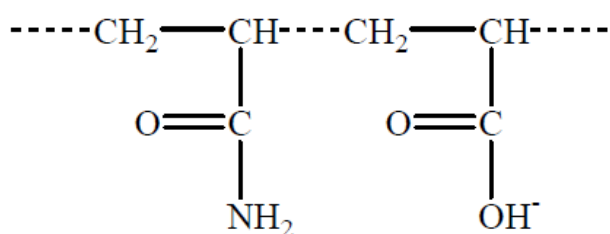
Figure 2.7 Molecular structure of anionic polyacrylamide (Green and Stott, 2001).

Polyacrylamide (PAM) is a well-known hydrogel. Commonly used as a super-absorbent, it can absorb more than 400 to 1,500 times its dry weight of water (Figure 2.7, Landis and Haase, 2012). PAM is a soil conditioner, which stabilizes soil aggregation and flocculate suspension. PAM has been used to help prevent soil erosion especially in furrow irrigation, on steep slopes during construction projects and in other disturbed areas, as well as for improving soil and water quality (Green and Stott, 2001). PAM has been greatly used in agriculture, both in nurseries and after out-planting. Although PAM can retain a lot of water close to large seeds and aid their germination, it may also inhibit germination, particularly of smaller seeds by reducing aeration and oxygen supply. Moisture supplied to seedling roots from PAM promotes fine root development by preventing desiccation. It may also promote production of natural polymeric mucilage from healthy roots (Figure 2.8). PAM is, therefore, often are mixed into growing media to increase water-holding capacity and reduce moisture stress (Landis and Haase, 2012).

Moisture Gradient
Soil Water -0.1 MPa
Hydrogel   -0.2 MPa
Root   -0.3 MPa
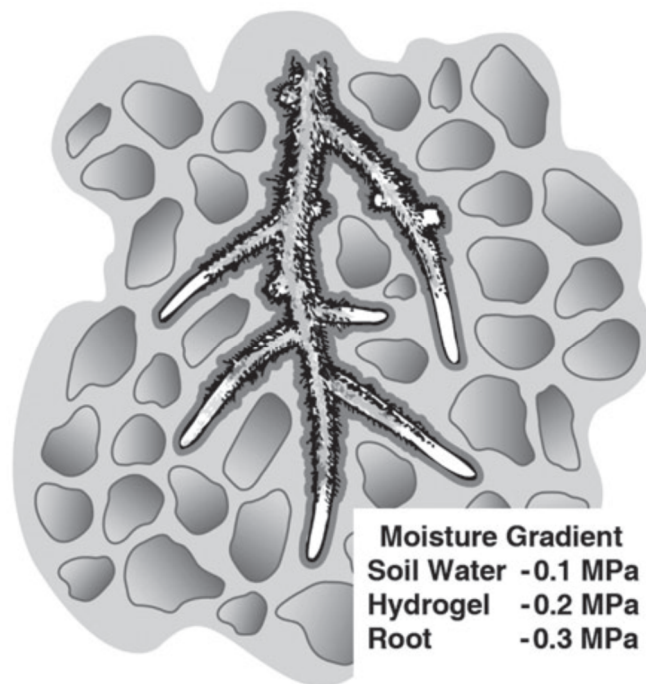
Figure 2.8 When hydrogels are applied as root dips, they function like the mucilage that is naturally produced by healthy roots and improve water uptake, by increasing root-to-soil contact and filling in air spaces (Landis and Haase, 2012)

Hydrogels have been studied, both in nurseries and in the field, especially for economic species. Numerous studies have shown that gels reduce drought stress. For example, *Pinus halepensis* seedlings perform better (shoot and root growth) in gels than in control growing media, when subjected to drought conditions (Hüttermann et al., 1999). Gels enhanced the drought tolerance capacity of *Conocarpus erectus* in arid and semi-arid areas (Al-Humaid and Moftah, 2007). Furthermore, media mixed with gel increase water-holding capacity (Akhter et al., 2004; Chirino et al., 2011) and seedling survival of *Quercus suber* (Chirino et al., 2011) and arable crops (wheat and barley) (Akhter et al., 2004) in field although it they had no effect germination of the latter (Akhter et al., 2004). In contrast, overdoses of hydrogel can cause mortality of pine seedlings, two years after planting. Hence, application rate must be carefully determined based on species and environmental variables (Sarvaš et al., 2007). Although the applications of hydrogel have been well explored for economic species, few forest and native tree species have been tested in nurseries and during direct seeding (Landis and Haase, 2012). Therefore, in the study presented below, I tested the effects of hydrogel on seed germination and seeding establishment both in the nursery and in the field during direct seeding.

2.8 Fertilizer Application

Mineral nutrients play key roles in plant growth and development, especially in physiological processes. Plants normally store nutrients in the seed for use during germination. External nutrient sources are important after seedling emergence. Plants naturally uptake nutrients from growing media (Jacobs and Landis, 2014). Therefore, providing sufficient nutrient is essential for plant growth. Mineral nutrients are often provided to plants in the nursery and during out-planting as fertilizer (FORRU, 2006; Hasse et al., 2014). Fertilizer application depends heavily on plant stage (seedling, sapling or adult) and nutrient availability in growing media.

Synthetic fertilizers can be categorized as soluble or controlled-release. Soluble fertilizers rapidly dissolve in water. Their main advantages are low cost and simple adjustment of nutrient rate of supply and ratio. However, since they dissolve fast, they drain rapidly from the system, so a lot of fertilizer fails to be up taken by the plants and they may cause pollution from leaching into water bodies (eutrophication). Controlled-release fertilizers are combined into pellets with less-soluble materials such as sulfur or a polymer.

The slow break down of the pellet regulates fertilizer release rate. This ensures more of the nutrients are taken up by the plants and less leaches into the environment (Table 2.4).

Table 2.4 Comparison of advantage and disadvantages of two majors types of synthetic fertilizers used in tropical plant nurseries (Jacobs and Landis, 2014)

Factor	Soluble fertilizer	Controlled-release fertilizer
1. Nutrient release rate	Very fast	Much slower-dependent on type and thickness of coating, as well as temperature and moisture
2. Number of application	Multiple-must be applied at regular intervals	Usually once per season, but additional top-dressing is an option
3. Uniformity of application	Good, but dependent on irrigation coverage	Can be variable if incorporated, resulting in uneven growth
4. Adjusting nutrient rates and ratios	Easy and quick	Difficult
5. Nutrient uptake efficiency	Poorer	Better
6. Leaching and pollution potential	Higher	Lower
7. Potential for fertilizer burn (salt toxicity)	Low if applied properly	Low, unless prills damaged during incorporation or following high temperatures
8. Product cost	Lower	Higher
9. Application cost	Higher	Lower

Controlled-release fertilizers have been used for native tree seedling production. FORRU-CMU recommends around 0.3 g of Osmocote, a slow release fertilizer, is applied at potting time and at 3-month intervals thereafter, to promote growth and ensure that the saplings are large enough by the optimum plating time (mid-June in northern Thailand) (FORRU, 2006). This amount and brand of fertilizer have been used since the unit was established (on the advice received during training in Australia). New coating technology is currently being developed, to reduce manufacturing costs and increase controlled-release efficiency. The National Nanotechnology Center (NANOTEC) is currently applying Nanotechnologies to produce new coating systems using a polyurethane

modified alkyd resin. It controls nitrogen release for up to 36 days while, uncoated fertilizer dissolves in water in only 5 minutes (Sitthisuwannakul1 et al., 2014). The product shows positive results in the laboratory, but it has not been tested on plants under more natural conditions and never with forest tree species. Consequently, one of the aims of the study described here was to test this new kind of fertilizer and compare its performance with that of FORRU-CMU's conventional fertilizer regime.

2.9 Preparing for Automated Restoration

The aim of the New York Declaration (described above), to restore forest to 350 million hectares of degraded land; an area large than India, by 2030 is hugely ambitious. A major limitation to achieving it is that sites available for restoration are often remote from access and are situated on steep, rugged terrain. Supportive technologies are, therefore, essential for restoring such enormous remote areas. Current aerial technologies are being developed to solve this problem. Lightweight Unmanned Aerial Vehicles (UAVs) or "drones" are being widely used for remote photography, surveys, logistics (Prime Air, new delivery system of AMAZON company by Drone, AMAZON, online, 2017) and can potentially be applied for restoring forest ecosystems (Elliott, 2016).

Drones could possibly be installed with equipment capable of carrying out various restoration tasks such as GPS, high-resolution cameras and tools to collect or deposit seeds or collect plant specimens, or to deliver fertilizer or spray pesticides (Elliott, 2017). Drones are highly cost-effective, being able to carry out tasks rapidly in remote rugged or dangerous locations, regardless of access problems and without employment of a lot of labour. Drones are becoming more and more affordable. Communities with limited funds can use this technology to enhance their ability in forest management and conservation (Paneque-Gálvez et al., 2014). Open access software such as "Ecosynth UAV" can effectively measure forest structure and complexity across landscapes using ordinary digital camera without the need for specialized sensors (Zahawi et al., 2015). Furthermore, in riparian forest, drones have been used to identify dead wood, canopy mortality and vegetation units via computer-aid visual images identification (Dunford, et al., 2009). Drones are now recommended as a useful component of ecologists' toolboxes, complementing traditional field tools (Zhang et al., 2016).

The latest imaging technologies allow drones to identify forest structure remotely. For forest restoration, they may become useful for various tasks, such as site preparation, planting, weed control, fertilizer application and monitoring etc. (Elliott et al., 2013; FORRU, 2006). However, use of drone technology is currently a huge knowledge gap. Native tree species have traditionally been used for conventional forest restoration because they have evolved to suite local ecosystem conditions (Elliott et al., 2013). However, which native tree species may be suitable for forest restoration by aerial seeding is still unclear. Transitioning from planting seedlings to dropping seeds from drones will require a quantum shift in forest restoration research. Firstly, testing which species to determine which may be suitable for aerial restoration is a high priority. The factors involved in ensuring survival of planted trees and those to ensure seed germination and early seedling establishment are very different. The first step is to test the relative performance of species during direct seeding, before taking the next step of testing them with aerial seeding. Direct seeding tests can be used to suggest which species would do well if dropped by drones. Dropping seeds in biodegradable "bombs" or encasing them in pelleting materials provides opportunities to greatly enhance germination and early seedling establishment. Media in bombs or pellets could include combinations of forest soil (to provide essential microbes) mixed hydrogels (to preserve moisture), predator repellants (to deter rats etc.) and fertilizer (to boost seedling growth immediately after germination. Testing all the "seed enabling technologies" will be essential to develop effective aerial seeding for forest restoration (Elliott, 2017).

All components of the study described below are, therefore, aimed at paving the way for a transition from traditional tree planting to aerial seeding by drones, seen as an essential step if large scale restoration is to be achieved in remote, rugged areas with the minimum of human intervention.

CHAPTER 3

Methodology

3.1 The study site

Direct seeding was carried out on a degraded site at Mon Cham, Mae Rim District, Chiang Mai (N 18° 56 ´ E 98° 49 ´, elevation 1,343). Annual rainfall (2015) was 1,324.0 mm. Rainy season normally start from May to October. The highest rainfall was found in August. Average temperature in 2015 was 21.5 °C. January was the coldest month, which had an average temperature 17.3 °C in 2015 (Figure 3.1). This area was previously used as agricultural land, but was subsequently earmarked for forest restoration by the Royal Project in 2012. Reforestation activities were funded by Plant a Tree Today Foundation in 2012 and by the Rajapruek Institute Foundation in 2013, with technical guidance from FORRU-CMU. The part of the site used for direct seeding experiments had not been planted with trees and was dominated by weeds such as *Pteridium aquilinum*, *Paspalum atratum* and *Imperata cylindrica* (Figure 3.2).
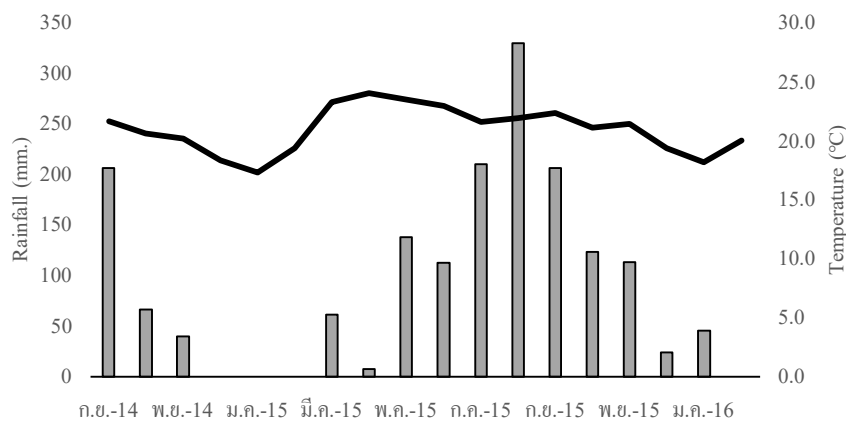
Figure 3.1 Average monthly rainfalls and temperatures at the study site, Mon Cham, Mae Rim District, Chiang Mai.

Germination and nursery experiments were carried out at the FORRU-CMU Nursery near Wat Prathat Doi Suthep.

Seed storage experiments were carried out at FORRU office in the Herbarium and Biology laboratory at Department of Biology, Chiang Mai University.

Figure 3.2 Study site at Mon Cham, Mae Rim District, Chiang Mai.

3.2 Species Selection and Seed Collection

Seeds of various native tree species were collected as they became available in every month of the year (Table 3.1) and subjected to three main experiments; immediate direct seeding in the degraded site at Mon Cham, seed storage and germination and seedling raising in the FORRU-CMU nursery.

Table 3.1 List of study species.

Species	Family	Date of seed collection	Diaspore use in this study	Storage Behaviour[3]
Acrocarpus fraxinifolius Arn.	Leguminosae	11/04/15	Seed[1]	N/A
Adenanthera microsperma Teijsm. & Binn.	Leguminosae	20/02/15	Seed[1]	N/A
Alangium kurzii Craib	Cornaceae	10/07/15	Pyrene[1]	N/A
Artocarpus lacucha Buch.-Ham.	Moraceae	01/06/15	Seed[1]	Probably Recalcitrant
Bauhinia variegata L.	Leguminosae	15/05/15	Seed[1]	Probably Orthodox
Castanopsis tribuloides (Sm.) A.DC.	Fagaceae	15/10/15	Seed[1]	Probably Recalcitrant
Choerospondias axillaris (Roxb.) B.L.Burtt & A.W.Hill	Anacardiaceae	12/07/15	Pyrene[1]	Probably Orthodox
Dimocarpus longan Lour.	Sapindaceae	01/10/14	Seed[1]	Recalcitrant
Diospyros glandulosa Lace	Ebenaceae	15/11/14	Seed[1]	N/A
Gmelina arborea Roxb.	Lamiaceae	21/05/15	Pyrene[1]	Orthodox
Horsfieldia glabra (Reinw. ex Blume) Warb.	Myristicaceae	19/05/15	Seed[1]	N/A
Hovenia dulcis Thunb.	Rhamnaceae	20/02/15	Seed[2]	Probably Orthodox
Manglietia garrettii Craib	Magnoliaceae	19/10/14	Seed[1]	N/A
Melia azedarach L.	Meliaceae	04/01/15	Seed[1]	Orthodox
Phyllanthus emblica L.	Phyllanthaceae	28/12/14	Seed[1]	Probably Orthodox
Prunus cerasoides Buch.-Ham. ex D.Don	Rosaceae	11/04/15	Pyrene[1]	Probably Orthodox
Spondias pinnata (L. f.) Kurz	Anacardiaceae	25/03/15	Pyrene[1]	N/A
Syzygium albiflorum (Duthie ex Kurz) Bahadur & R.C.Gaur	Myrtaceae	02/06/15	Seed[1]	N/A

[1] Gardner et al., 2000
[2] Kopachon et al., 1996
[3] Seed information database (SID), Royal Botanic Gardens Kew, 2017
N/A information not available

3.3 Seed Biology

3.3.1 Baseline Germination

A standard nursery germination test was carried out. Three replicates of 50 seeds were prepared in modular plastic trays with 100% forest soil. The seeds were buried about 1 cm in the media. The number of germinated seeds was counted every 7 days as well as the number of seedlings which subsequently died. Germination was defined as visual emergence of a plumule or radical through the testa. Graphs were plotted of cumulative numbers of seeds germinated and numbers of seedlings which subsequently dies vs time. Mean and variability of germination percentage and median length of dormancy (MLD) were calculated. MLD is defined as the time taken for germination of half the number of seeds that finally germinated. Germination test was monitored until 30 days after the last germination recorded.

3.3.2 Moisture Content

The moisture content (MC) test followed the ISTA rules (ISTA, 2006). Three replicates of 10 to 15 seeds were randomly selected and weighed with a digital scale accurate to $1/10,000^{th}$ of a gram, then dried at $103 \pm 3 \,°C$ for 17 ± 1 h, in hot air oven. Seed moisture content was calculated on a fresh weight basis (Schmidt, 2007).

$$\text{Moisture content (\%)} = \frac{(\text{Wet weight} - \text{Dry weight}) \times 100}{\text{Wet weight}}$$

3.4 Seed Storage

3.4.1 Seed Storage Behaviour

Seed storage behaviour was tested following the methods of Hong and Ellis (1996). The initial moisture content of seeds was determined and the moisture content was reduced to 10% MC. The germination was tested. Seed moisture content could then be reduced 5 % and the seeds stored at room temperature or -20 °C and germination was tested again. Seeds were separated into endocarp or testa and embryo or endosperm parts and were dried under the above conditions. The dry weight of the covering parts and embryo were used to calculated seed coat ratio and the probability of the sensitivity of the seeds to desiccation.

3.4.2 Seed Storage Design

Longevity under storage was determined, using seeds stored in hermetically sealed polyethylene bags under various conditions; i) at initial seed moisture content or ii) reduced to 5% moisture content either under ambient conditions or in a refrigerator (4 °C). Seed germination tests were then carried out on three replicates of 30 seeds and monitored every 1, 3, 6, and 12 month(s) (Figure 3.3).

3.4.3 Statistical Analysis

Differences in mean percent seed germination and MLD (days) among storage treatments and species were tested with ANOVA, followed by pair-wise t-tests, when indicated. Binomial data, such as percent germination, were arcsine-transformed before analysis.
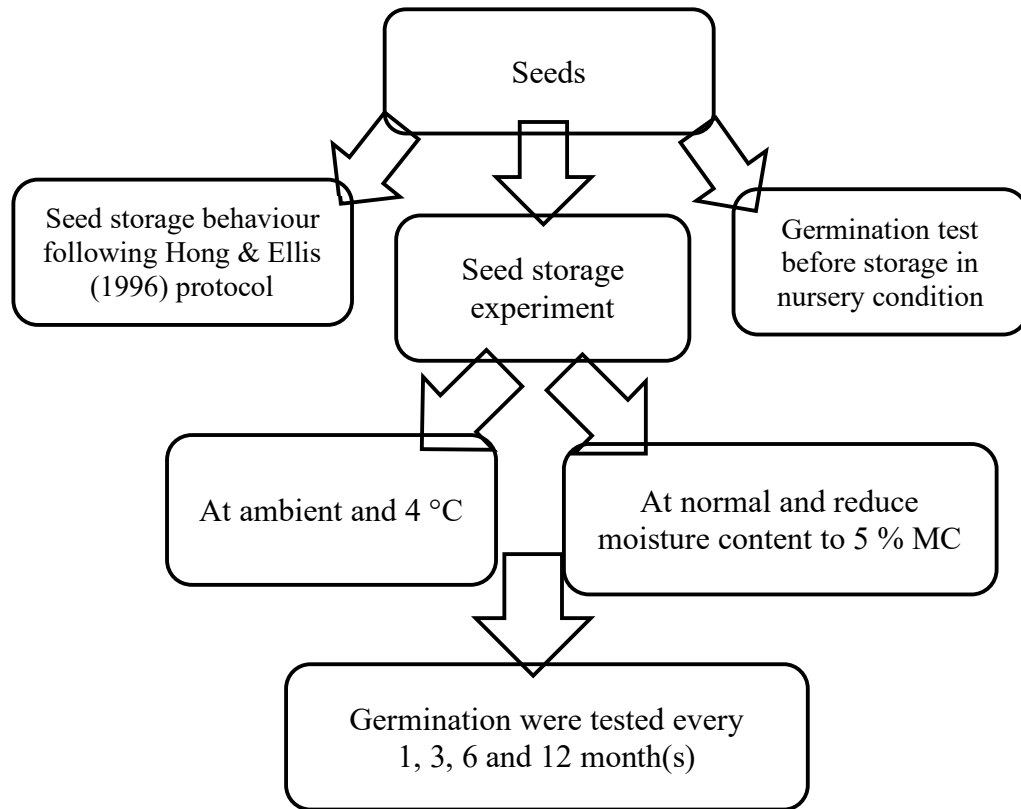
Figure 3.3 Diagram of seed storage experiment.

3.5 Field Trial

3.5.1 Direct Seeding

Seeds of native species were sown in the study site, immediately after seed collection. Seeds were positioned 50 cm apart and buried as three replicates of 50 seeds each, with at least 20 meters between each replicate. A PVC pipe was placed around every seed sown to prevent seed movement and to make the seeds easier to find for future measurements. Stored seeds were sown beside immediately sown seeds at the beginning of rainy season (12th June 2015) in a paired experimental design. Seeds of *A. kurzii* (29th July 2015) and *S. axillaris* (15th July 2015) were sown later, because they fruited during the rainy season. Seed germination was monitored weekly, until germination ceased and MLD subsequently calculated. In addition, height, root collar diameter (RCD) and crown width of surviving seedlings were monitored at beginning of first rainy season (July, 2015)

and after first rainy season (December, 2015) and beginning of second rainy season (July, 2016) (Figure 3.4).
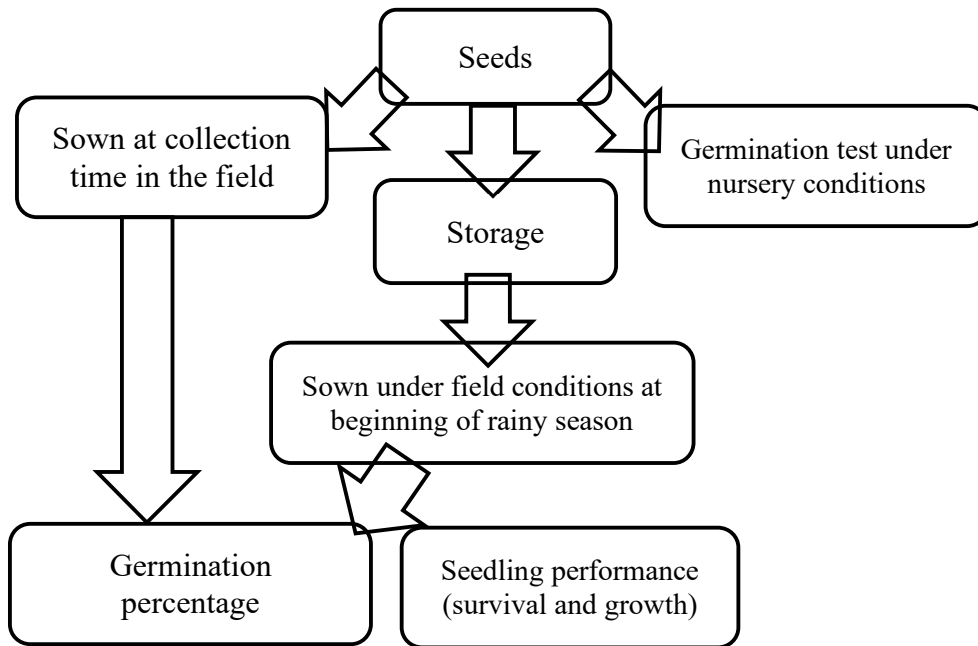
Figure 3.4 Diagram of direct seeding experiment.

3.5.2 Direct-seeded Seedlings vs Nursery-raised Seedlings

Seedlings, raised in the nursery for about 1 year, under standard nursery conditions and approximately 30-50 cm tall, were planted next to seedlings that had establish in the field in the direct seeding experiments, in a pair-wise experiment. Seedling Survival and growth of both nursery-raised and direct seeded seedlings were monitored and compared using paired t-tests. Weeds on the study site were controlled at the beginning and late rainy season, summer and winter season. Fertilizer was applied to seedlings following the recommendations of FORRU (2006).

Seedling relative growth rate (RGR) was calculated using follow equation:

$$RGR = \frac{\ln FS - \ln IS \times 36,500}{No.\ days\ between\ measurements}$$

Where in ln FS was natural logarithm of final sapling growth and ln IS was natural logarithm of initial sapling growth (Elliott et al., 2013).

Sturdiness quotient was calculated using follow equation (Elliott et al., 2013):

$$\text{Sturdiness quotient} = \frac{\text{Height (cm)}}{\text{RCD (mm)}}$$

A Relative Species Performance Index was calculated by three different methods:
i) Index was calculated from mean percent yield multiplied by absolute seedling height (cm) after one year. The highest score was ranked as 100 and the others expressed as a percentage of the highest score (Tunjai and Elliott, 2012) as following equation:

$$\text{Row score} = \% \text{ Yield x Height (cm)},$$

$$\text{Index} = \frac{\text{Row score x } 100}{\text{Highest row score}}$$

ii) The calculation method was modified from Tunjai and Elliott (2012) by using height RGR (%/year) instead of absolute height as follows:

$$\text{Raw score} = \% \text{ Yield x Height RGR (\%/year)},$$

$$\text{Index} = \frac{\text{Raw score x } 100}{\text{Highest raw score}}$$

iii) An index was devised which combined both survival and growth into a single indicator. The index was calculated from the relative yield, combined with relative growth index, based on seedling volume and crown width. Species values were ranked in declining order of performance.

$$\text{Growth index} = (1/3 \, \pi \text{ x } r^2 \text{ x H}) + \text{RCR Crown width},$$

Where RGR is root collar diameter divided by 2 and H = RGR height

$$\text{Index} = \frac{\text{Relative yield} + \text{Relative growth index}}{2}$$

3.5.3 Statistical Analysis

Mean percent seed germination, MLD (days) both in the field and in the nursery at seed collection time and after storage, were compared using ANOVA and t-tests for multiple and pair-wise comparisons among species and treatments respectively. Binomial data, such as percent germination, survival and yield, were arcsine-transformed before analysis. Differences in growth parameters, both absolute numbers and relative values were also compared, using ANOVA, followed by t-tests. Correlation analysis was performed to determine relationships between mean absolute growth parameters (height crown width and RCD) and relative growth rates (height crown width and RCD). In addition, mean relative growth rate (height, crown width and RCD) of direct-seeded seedlings and nursery-raised seedlings were tested with paired t-tests.

3.6 Hydrogel Experiment

In July 2015, seeds of six native tree species (*Acrocarpus fraxinifolius, Artocarpus lacucha, Choerospondias axillaris, Gmelina arborea, Phyllanthus emblica,* and *Prunus cerasoides*) were sown into five media treatments, including 100% forest soil, mixtures of forest soil and 10, 20 and 30 % polyacrylamide gel or hydrogel $(C_3H_5NO)_n$ and a half-layer of hydrogel and forest soil (Figure 3.5). Seeds were sown in 2-inch diameter PVC pipes, 30 seeds per treatment per replicate (150 seeds per species per replicate) and three replicates were placed across the degraded site at Mon Cham. The field results were compared with the results of nursery germination tests (also three replicates of 30 seeds each in modular germination trays, in July 2015). Weekly monitoring of seed germination was continued until no further germination had been recorded for 4 consecutive weeks. In the field, in December 2015, baseline measurements of seedling height, root collar diameter (RCD) and crown width of surviving seedlings were made and the measurements were repeated in July 2016 (to calculate RGR). Seedling growth was not measured for the seedlings which germinated in the nursery.
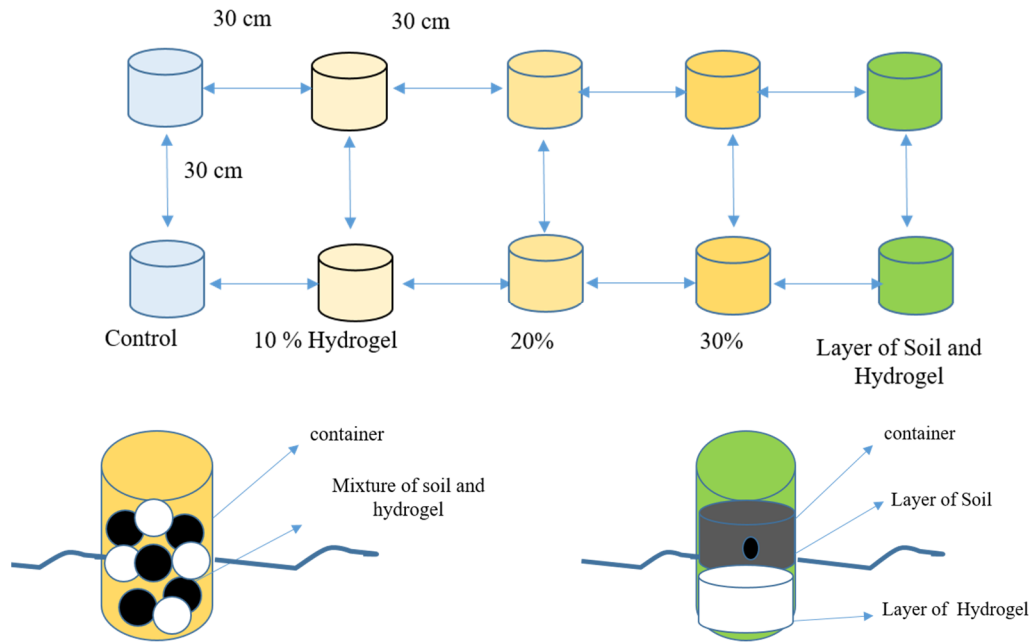
Figure 3.5 Diagram of hydrogel experiment.

3.6.1 Statistical Analysis

Differences in mean percent seed germination and MLD (days) between sites (nursery and field) were tested with t-tests. Mean differences in germination, MLD, survival, yield and growth between hydrogel treatments were identified with ANOVA followed by *post-hoc* analyses, using Tukey's HSD at $\alpha=0.05$. Binomial data (percent germination, survival and yield) were arcsine-transformed before analyses. Species performance indices were calculated as described above.

3.7 Fertilizer Experiment

Experiments were performed in the nursery on saplings of eight indigenous forest tree species: *Acrocarpus fraxinifolius, Adenanthera microsperma, Artocarpus lacucha, Hovenia dulcis, Horsfieldia glabra* and *Phyllanthus emblica, Prunus cerasoides* and *Syzygium albiflora*. Seeds were germinated in modular germination trays with 100% forest soil. Seedlings with at least two pairs of true leaves were then transferred into black polyethylene bags (9 x 2 ½ inches). A mix of forest soil, coconut husk and peanut husk (2:1:1) was used as the standard potting medium (FORRU, 2006; Elliott et al., 2013).

Seedlings were prepared at least two weeks before starting the experiment to take account of mortality due to transplantation stress, so only healthy seedlings were used in the study.

3.7.1 Experimental Design

To quantify the effectiveness of fertilizer on seedling growth performance and determine nutrient allocation within the plants, the saplings were tested with three fertilizer treatments in a randomized completed block design experiment. The effects of Osmocote (FORRU's standard fertilizer treatment) and a new fertilizer developed by The National Nanotechnology Center (NANOTEC, hereafter referred to as NF). Both are slow release fertilizers, with nitrogen, phosphorus and potassium at 13, 13, and 13 % respectively. However, NF differs from Osmocote in that it has a nanocomposite coating; an alkyd resin, containing modified montmorillonite clay (mMMT), which, combined with a hydrophobic polymer layer, decelerates the solubility of fertilizer within, thus delivering a more even supply of nutrients to the plants and reducing nutrient wastage (Sitthisuwannakul1 et al., 2014). Osmocote (0.3 gram) was used as the control, since this is the standard protocol used by FORRU-CMU. It was tested against two dose sizes of NF, (0.15 and 0.3 g).

Seedlings were arranged in 3 blocks, each containing the two NF treatments and one Osmocote control. Within each replicate, seedlings were arranged in squares of 5 x 5 seedlings, within which 3 x 3 seedlings were used as the test seedlings, with the outliers forming a "guard row", to control for seedling position and buffering against external factors (Figure 3.6). So, 225 seedlings were used to form all three blocks, of which 81 were the test plants. In order to quantify soil nutrient availability, one extra block was set up with only media and fertilizer (Figure 3.7).

Figure 3.6 Fertilizer experimental design.

Figure 3.7 Diagram of fertilizer experiment.

3.7.2 Fertilizer Analysis

Nutrients availability in the different treatments were analyzed at the start of the experiment and at 56 and 112 days respectively. Available nitrogen, phosphorus and potassium were compared among the treatments. The media were sampled from at least one pot from each treatment and block for each species. So at least three samples were tested for each treatment and species. Furthermore, the medium from an extra block (media with only fertilizer excluded seedling) was also analyzed in order to remove the effects of nutrient uptake by the plants, thus allowing a crude estimate of nutrient uptake to be made. All samples were analyzed at central laboratory of Department of Plant Science and Soil Science, Faculty of Agriculture, CMU.

3.7.3 Seedling Growth Performance

The following variables were measured for all test seedlings: root collar diameter, crown width (at widest point), height, and health (on a scale 0-3) (FORRU, 2006). Root: shoot ratio was also determined as below equation at the beginning of the experiment and after 56, 112 and 187 days respectively.

$$\text{Root: shoot ratio} \;=\; \frac{\text{Root dry weight (g)}}{\text{Shoot dry weight (g)}}$$

Seedlings were randomly selected from each treatment and block, thoroughly removed and roots and shoots separated and weighed, dried (at 70°C until constant weight) and then weighed again.

3.7.4 Statistical Analysis

Mean relative growth rate (height, crown width and RGR), seedling biomass, root-shoot ratio and fertilizer reaming were compared with ANOVA. The differences between pairs were identified by Tukey's HSD at $\alpha=0.05$.

CHAPTER 4

Results

4.1 Seed Biology

4.1.1 Seed Germination and Median Length of Dormancy

Percent germination in the nursery was calculated from three replicates of 50 seeds of 17 native tree species. The mean (± SE) percentage across all species was 44.7 ± 3.6 %, ranging from 6 to 92 %. *Gmelina arborea* (6.0 ± 1.2 %) germinated the least, whereas *Artocarpus lacucha* (92.0 ± 2.0 %) germinated the most (Table 4.1). Species could be divided into 3 groups, according their germination: 1) low germination (<30 %): *Dimocarpus longan*, *Diospyros glandulosa*, *Gmelina arborea* and *Spondias pinnata,* 2) intermediate germination (30-60%): *Acrocarpus fraxinifolius*, *Alangium kurzii*, *Choerospondias axillaris*, *Hovenia dulcis*, *Manglietia garrettii*, *Melia azedarach, Phyllanthus emblica* and *Syzygium albiflorum* and 3) high germination (>60 %): *Adenanthera microsperma*, *Artocarpus lacucha*, *Bauhinia variegata*, *Horsfieldia glabra* and *Prunus cerasoides*.

The selected native tree species showed various lengths of dormancy. The average dormancy across species was 69.4 ± 8.2 days, ranging from 8 to 244 days (depending on species). *C. axillaris* exhibited the longest dormancy (244.5 ± 14.1 days), whilst *B. variegata* had the shortest (8.0 ± 0.1 days). The species tested could be divided into 3 groups, based on median length of dormancy (MLD): 1) a short-dormancy group (MLD <30 days): *A. microsperma*, *A. lacucha*, *Bauhinia variegata*, *D. longan*, *G. arborea* and *S. pinnata*; 2) an intermediate-dormancy group (MLD 30-100 days): *A. kurzii, C. tribuloides, H. glabra, H. dulcis, M. azedarach, P. cerasoides* and *S. albiflorum* and 3) a prolonged-dormancy group (MLD >100 days): *A. fraxinifolius, C. axillaris, D. glandulosa* and *P. emblica.*

Table 4.1 Percent seed germination, median length of dormancy (MLD), initial seed moisture content (MC) and seed mass of 17 native tree species in a nursery in northern Thailand. Germination and MLD calculated from nursery experiments with 3 replicates of 50 seeds each. Seed MC calculated from three replicates of 15 dried seeds. Dry seed mass averaged from 20 dried seeds.

Species	Sowing date	Germination (%)		MLD (days)		Seed MC (%)		Dry seed mass (g)	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE
Acrocarpus fraxinifolius	11/04/15	43.3	8.7	118.3	6.7	10.3	0.1	0.034	0.001
Adenanthera microsperma	26/02/15	68.7	4.4	23.3	2.0	7.1	0.2	0.102	0.003
Alangium kurzii	14/07/15	52.0	6.1	53.0	0.0	16.1	0.2	0.148	0.016
Artocarpus lacucha	04/06/15	92.0	2.0	24.8	5.3	46.4	1.2	0.353	0.017
Bauhinia variegata	22/05/15	85.3	3.7	7.8	0.1	10.7	0.1	0.275	0.012
Choerospondias axillaris	14/07/15	46.7	6.8	244.3	8.1	20.6	1.0	1.700	0.080
Dimocarpus longan	02/10/14	8.7	0.7	17.0	2.3	43.4	1.3	0.378	0.026
Diospyros glandulosa	18/11/14	8.7	3.5	128.3	1.8	44.2	0.3	0.149	0.005
Gmelina arborea	26/05/15	6.0	1.2	23.3	2.0	13.3	0.1	0.432	0.032
Horsfieldia glabra	20/05/15	63.3	3.7	35.0	0.4	18.0	1.0	3.800	0.124
Hovenia dulcis	26/02/15	34.7	7.9	73.0	2.9	7.9	0.2	0.023	0.001
Manglietia garrettii	23/10/14	49.3	5.3	106.7	6.3	15.2	0.6	0.052	0.001
Melia azedarach	05/01/15	31.3	3.5	79.2	2.3	10.6	0.2	0.048	0.001
Phyllanthus emblica	05/01/15	38.7	5.9	107.0	5.5	10.8	0.1	0.024	0.001
Prunus cerasoides	11/04/15	64.0	1.2	46.3	21.4	19.5	0.3	0.229	0.007
Spondias pinnata	30/03/15	18.0	5.0	26.4	3.0	8.4	0.1	6.370	0.362
Syzygium albiflorum	04/06/15	49.3	2.7	66.3	2.4	35.7	0.8	1.636	0.060

A. fraxinifolius and *A. microsperma* seeds were subjected to an additional experiment to trial the effects of seed scarification; a treatment known to shorten MLD. Seed scarification had no significant effect on percent seed germination in *A. microsperma* (control seeds 68.7 ± 4.4 %, scarified seeds 59.3 ± 1.8 %, *t*-test, *p*=0.12), but it did significantly reduce MLD by 14 days on average, from 23.3 ± 2.0 days (control) to 9.0 ± 1.0 days (*t*-test, *p*< 0.01). For *A. fraxinifolius* seeds, the treatment both significantly increased germination and shortened dormancy. Percent germination increased by 45 % from 43.3 ± 8.7 % for control seeds to 88.9 ± 2.9 % for scarified seeds *t*-test, *p*<0.01). MLD was shortened by 99 days, on average, from 118.3 ± 6.7 days for the control seeds to only 9.0 ± 0.0 days for scarified seeds (*t*-test, *p*< 0.01).

It appeared that species that germinated rapidly also tended to have higher germination percentages, but regression analysis showed that the correlation was neither strong nor significant (*r*=0.43, *p*=0.08, N=17, Figure 4.1).
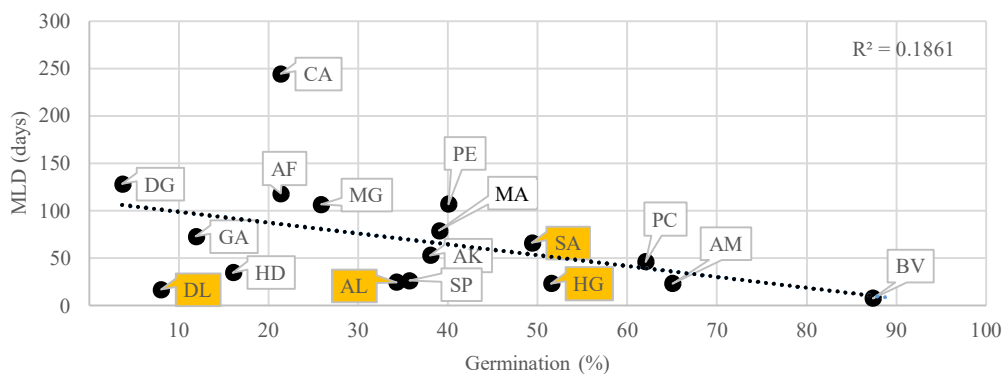
Figure 4.1 Relation of mean percent germination and median length of dormancy (MLD) of 17 tree species in the nursery condition. Plotted by species (N=17). Dotted line is a trend of relation. Orange boxes indicate recalcitrant species and white boxes are orthodox; AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa,* GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MG=*M. garrettii*, MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

Species were grouped according to germination performance and length of dormancy (Table 4.2). *D. longan, G. arborea* and *S. pinnata* formed a low-germination/short-dormancy group, whereas *A. microsperma, A. lacucha* and *B. variegata* formed a high-germination/short-dormancy group. Four species, *A. kurzii, H. dulcis, M. azedarach* and *S. albiflorum* formed an intermediate-germination/intermediate-dormancy group, whilst *H. glabra* and *P. cerasoides* formed a high-germination/intermediate-dormancy group. *A. fraxinifolius, C. axillaris, M. garrettii* and *P. emblica* formed an intermediate-germination/prolonged-dormancy group. Only a single species, *D. glandulosa,* had both low-germination and prolonged dormancy.

Table 4.2 Categories of percent germination and median length of dormancy (MLD) of 17 tree species in the nursery condition.

MLD [a] (days)	Germination percent [b]		
	Low	Intermediate	High
Short	*D. longan* *G. arborea* *S. pinnata*		*A. microsperma,* *A. lacucha* *B. variegata*
Intermediate		*A. kurzii* *H. dulcis* *M. azedarach* *S. albiflorum*	*H. glabra* *P. cerasoides*
Prolonged	*D. glandulosa*	*A. fraxinifolius* *C. axillaris* *M. garrettii* *P. emblica*	

[a] Short-dormancy (MLD < 30 days); intermediate (MLD 30-100 days); prolonged (MLD > 100 days)

[b] Low-germination (< 30 %); intermediate (30-60 %); high (> 60%)

4.1.2 Seed Mass and Seed Moisture Content

Propagules, dispersed by forest trees (or "dispersal units"), are not always just seeds. Sometimes, they include the inner fruit wall (endocarp) surrounding one or several seeds. These structures are termed "pyrenes". In this study, I include pyrenes along with seeds (as they are both units of dispersal). Four of the study species were dispersed as pyrenes. *P. cerasoides* produces single seeded pyrenes ("cherry stones"), *G. arborea* produces 1-4 seeded pyrenes, whilst, *C. axillaris* and *S. pinnata* produce pyrenes, containing up to a maximum of 5 seeds.

S. pinnata produced the heaviest seeds (mean dry mass 6.370 ± 0.362 g), whilst *H. dulcis* produced the lightest (0.023 ± 0.001 g, Table 4.1). The seeds of 5 species were categorized as small (0.01-0.099 g) (following the protocol of Doust, *et al.* (2006)): *A. fraxinifolius*, *H. dulcis*, *M. garrettii*, *M. azedarach* and *P. emblica*. The majority of the studied species (12 of 17) had seeds of intermediate size (0.1-4.99 g): *A. microsperma, A. kurzii, A. lacucha, B. variegata, C. tribuloides, C. axillaris, D. longan, D. glandulosa, G. arborea, H. glabra, H. dulcis, P. cerasoides* and *S. albiflorum* and only one species, *S. pinnata,* had large seeds (>5.0 g).

Seed moisture content (MC) varied from 7 % to 46.6 % MC (Table 4.1). The seeds of 3 of the studied species had very low MC: *A. microsperma* (7.1 ± 0.2 %,), *H. dulcis* (7.9 ± 0.2 %) and *S. pinnata* (8.4 ± 0.1 %). In contrast, *A. lacucha* (46.4 ± 1.2 %) contained the highest moisture content.

4.2 Seed Storage

Tests of seed storage properties were carried out on 17 native tree species. Species were then classified by storage behaviour, following Hong and Ellis (1996). Seeds of the studied species were sown at the initial moisture content, immediately after collection, then dried to 10 % and 5% MC and stored at 5% MC at -20 °C. The percent germination and dormancy were compared among moisture content levels. *S. pinnata* was excluded from the storage behaviour classification due to the difficulty of reducing the moisture content of its pyrenes - the largest of the diaspores in this study, as previously mentioned, but was included in tests of storage conditions without seed moisture content reduction. *Castanopsis tribuloides* was an additional species tested from the direct seeding study.

4.2.1 Seed Storage Behaviour

The viability of seeds of 10 species: *A. microsperma, A. kurzii, B. variegata, C. axillaris, G. arborea, H. dulcis, M. garrettii, M. azedarach, P. emblica* and *P. cerasoides* was not significantly reduced after storage at 5% MC at -20 °C for a month. This group was classified as orthodox i.e. no loss of viability after storage at sub-zero temperatures for a long duration. *A. fraxinifolius* significantly lost viability, when the seeds were dried to 5% MC and stored at -20 °C (ANOVA, *p*=0.02, Table 4.3). *D. glandulosa* could be dried to 10% MC, but they totally lost viability when dried to 5% MC and stored at -20 °C. These two species were, therefore, classified as intermediate. Seeds of five species; *A. lacucha, C. tribuloides, D. longan, H. glabra* and *S. albiflorum* were very sensitive to desiccation and freezing, completely losing viability when dried to 10% and 5% MC. These species were classified as recalcitrant (Table 4.3).

Table 4.3 Effects of drying and freezing on initial germination of 17 tree species, Seed were reduced to different moisture contents (MC). Germination percentages are means of 3 replicates (30 seeds per replicate), under nursery conditions.

Species	Initial MC (%)		Initial germination (%)			Germination of seeds with10% MC (%)			Germination of seeds with 5% MC (%)			Germination of seeds with 5% MC and stored at -20 °C for 1 month (%)		p
	Mean	SE	Sowing date	Mean	SE	Sowing date	Mean	SE	Sowing date	Mean	SE	Mean	SE	
Orthodox														
Adenanthera microsperma	7.1	0.2	26/02/15	59.3[b]	1.8		-	-	19/03/15	47.8[ab]	8.0	76.7[a]	1.9	0.01
Alangium kurzii	16.1	0.2	14/07/15	52.0[a]	6.1	31/07/15	50.0[a]	3.3	07/08/15	15.6[b]	1.1	37.8[a]	2.9	<0.01
Bauhinia variegata	10.7	0.1	22/05/15	85.3[a]	3.7		-	-	02/06/15	62.2[b]	4.8	76.7[ab]	1.9	0.01
Choerospondias axillaris	20.6	1.0	14/07/15	46.7	6.8				30/07/15	-	-	33.3	5.1	0.19
Gmelina arborea	13.3	0.1	26/05/15	6.0	1.2		-	-	02/06/15	7.8	1.1	3.3	1.9	0.21
Hovenia dulcis	7.9	0.2	26/02/15	34.7[ab]	7.9		-	-	30/03/15	50.0[a]	3.3	21.1[b]	2.2	0.02
Manglietia garrettii	15.2	0.6	23/10/14	49.3[ab]	5.3	24/01/14	68.9[a]	6.8	19/03/15	43.3[ab]	3.8	32.2[b]	7.8	0.02
Melia azedarach	10.6	0.2	05/01/15	31.3	3.5		-	-	10/03/15	28.9	3.9	11.1	5.9	0.08
Phyllanthus emblica	10.8	0.1	05/01/15	38.7[a]	5.9		-	-	16/03/15	13.3[b]	1.9	25.6[ab]	6.8	0.04
Prunus cerasoides	19.5	0.3	11/04/15	64.0[ab]	1.2	14/04/15	54.4[b]	9.7	30/04/15	82.2[a]	2.2	81.1[a]	2.2	0.01
Intermediate														
Acrocarpus fraxinifolius	10.3	0.1	11/04/15	88.9[a]	2.9		-	-	20/04/15	56.7[b]	6.9	60[b]	8.8	0.02
Diospyros glandulosa	44.2	0.3	18/11/14	8.7	0.3	28/11/14	16.7	1.9	03/02/15	0	0	0	0	0.15
Recalcitrant														
Artocarpus lacucha	46.4	1.2	04/06/15	92.0	1.2	14/06/15	0	0	18/06/15	0	0	0	0	
Castanopsis tribuloides	33.6	0.6	16/10/15	62.7	0.6	18/11/15	0	0	25/11/15	0	0	0	0	
Dimocarpus longan	43.4	1.3	02/10/14	8.7	1.3	7/10/14	0	0	14/10/14	0	0	0	0	
Horsfieldia glabra	18.0	1.0	20/05/15	63.3	1.0	01/07/16	0	0	17/10/15	0	0	0	0	
Syzygium albiflorum	35.7	0.8	04/06/15	49.3	0.8	19/07/15	0	0	21/07/15	0	0	0	0	

-Superscript letters indicate statistically different within species (mean differentiation using Turkey's HSD, α= 0.05).

Mean dormancy of *D. glandulosa*, *G. arborea* and *P. cerasoides* was not significantly affected by the storage treatments (ANOVA, p=0.18, 0.08 and 0.24 respectively, Table 4.4). In contrast, mean dormancy length of *B. variegata*, *C. axillaris*, *H. dulcis*, *M. garrettii*, *M. azedarach* and *P. emblica* significantly declined with reduced seed moisture content (Table 4.4). *A. fraxinifolius* was the only species with significantly longer dormancy when seeds were stored at 5% MC and -20 °C (ANOVA, p<0.01, Table 4.4)

Table 4.4 Effects of drying and freezing on initial median length of dormancy (MLD) of 17 tree species, Seed were reduced into different moisture contents (MC). MLD were shown in the table, calculated from three replicates of 30 seeds in the nursery condition.

Species	Initial MLD (days)		MLD of seeds with 10% MC (days)		MLD of seeds with 5% MC (days)		MLD of 5% MC and stored at -20 °C for 1 month (days)		p
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
Orthodox									
Adenanthera microsperma	9.0[ab]	1.0	-	-	12.1[a]	0.4	8.0[b]	0.6	0.02
Alangium kurzii	53.0[ab]	0.0	33.9[b]	4.0	61.0[ab]	13.7	73.8[a]	3.9	0.03
Bauhinia variegata	7.8[a]	0.1	-	-	5.0[b]	0.2	4.6[b]	0.1	<0.01
Choerospondias axillaris	244.3[*]	8.2	-	-	-	-	46.0	23.0	<0.01
Gmelina arborea	23.3	2.0	-	-	6.0	1.5	14.7	7.3	0.08
Hovenia dulcis	73.0[a]	1.9	-	-	15.7[b]	0.6	16.5[b]	2.5	<0.01
Manglietia garrettii	106.7[a]	6.3	66.1[b]	10.2	30.4[c]	0.7	30.5[c]	0.5	<0.01
Melia azedarach	79.2[a]	2.3	-	-	38.3[ab]	4.9	31.9[b]	16.0	0.03
Phyllanthus emblica	107.0[a]	5.5	-	-	62.2[b]	2.8	57.9[b]	0.3	<0.01
Prunus cerasoides	46.3	21.4	35.6	14.7	13.3	0.3	11.4	0.6	0.24
Intermediate									
Acrocarpus fraxinifolius	9.0[b]	0.0	-	-	5.0[c]	0.0	16.7[a]	0.3	<0.01
Diospyros glandulosa	128.3	1.8	122.1	5.8	-	-	-	-	0.18
Recalcitrant									
Artocarpus lacucha	24.8	9.2	-	-	-	-	-	-	-
Castanopsis tribuloides	51.2	8.3	-	-	-	-	-	-	-
Dimocarpus longan	17.0	2.3	-	-	-	-	-	-	-
Horsfieldia glabra	35.5	0.4	-	-	-	-	-	-	-
Syzygium albiflorum	66.3	2.4	-	-	-	-	-	-	-

-An asterisk (*) in row indicates statistical difference between seed moisture contents within species (*t*-test, $p < 0.05$).
-Superscript letters indicate statistically different within species (mean differentiation using Turkey's HSD, α= 0.05).

4.2.2 Storage Duration

In this section, I examine in more detail the storage behaviour of each species over 12 months' storage.

4.2.2.1 *Acrocarpus fraxinifolius*

Storage over 12 months had no effect on germination percent of *A. fraxinifolius* seeds, but it did significantly accelerate germination. Mean germination percent of seeds with normal moisture content (control) was 88.9 ± 1.9 % (significantly different compared with all other storage conditions; ANOVA, p=0.53, Figure 4.2 a). MLD was significantly reduced under all storage conditions over 12 months (ANOVA, p<0.01, Figure 4.2 b).

Figure 4.2 Mean percent seed germination and median of dormancy (MLD) of *A. fraxinifolius* in different moisture contents (normal (NMC) and 5% (5% MC)), storage temperatures (ambient (A) and refrigerator, 5 °C (R)) and storage durations (0, 1, 6 and 12 months), testing in nursery with 3 replicates of 30 seeds, a) Germination and b) MLD.

4.2.2.2 *Adenanthera microsperma*

Storage increased germination and accelerated it. Refrigeration without drying was the best treatment. Mean percent germination of control seeds was 59.3 ± 1.8 %. Seeds with 5% MC stored at refrigerator total lost viability after 12 months' storage. Mean germination of normal MC seed, stored at refrigerator had the highest percent germination ($82.2\pm2.9\%$) compared to control and 5% MC stored at ambient temperature (ANOVA, $p=0.01$, Figure 4.3 a). Mean MLD was significantly reduced after 12 months' storage (ANOVA, $p<0.01$, Figure 4.3 b).

Figure 4.3 Mean percent seed germination and median of dormancy (MLD) of *Adenanthera microsperma* in different moisture contents (Normal (NMC) and 5% (5% MC)), storage temperatures (ambient (A) and refrigerator, 5 °C (R)) and storage durations (0, 1, 3, 6 and 12 months), testing in nursery with 3 replicates of 30 seeds, a) Germination and b) MLD.

4.2.2.3 *Alangium kurzii*

Storage under ambient temperatures killed all or most *A. kurzii* seeds, within 6 months, whereas refrigeration allowed both dried and NMC seeds to survive with no significant decline in germination percent. The control seeds had 46.2 ± 2.2 % germination. Mean germination of seeds with NMC and 5% MC stored at refrigerator showed no significant differences with control (ANOVA, *p*=0.02, Figure 4.4 a). Mean dormancy of 5% MC at refrigerator was the longest, while 5% MC seeds was the shortest (ANOVA, *p*=0.02, Figure 4.4 b).
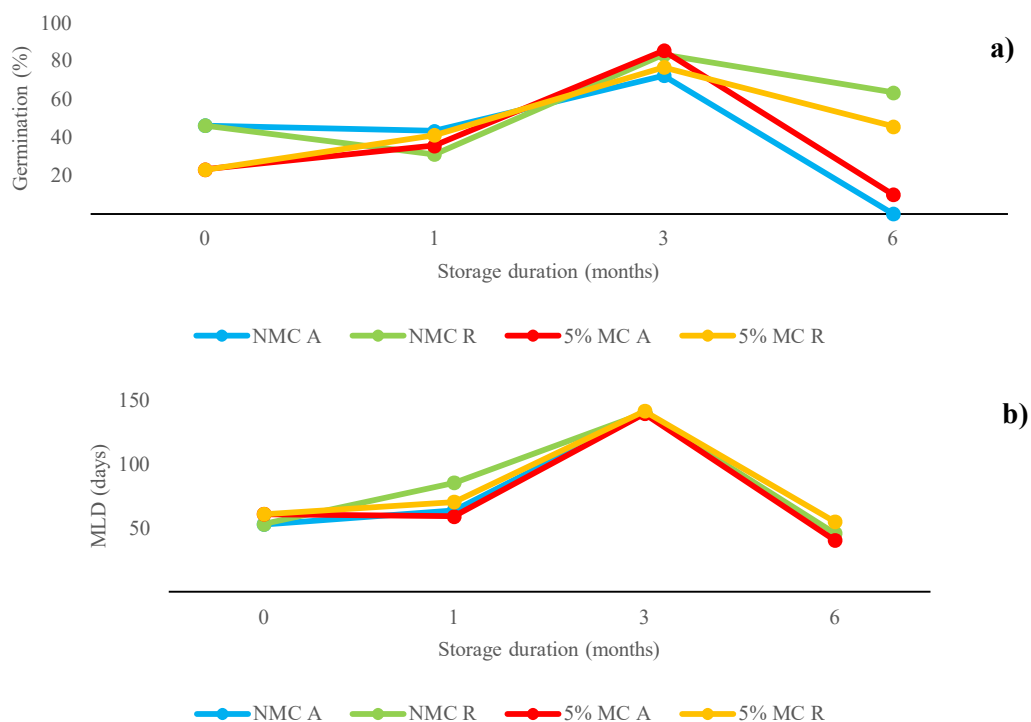
Figure 4.4 Mean (±) percent seed germination and median of dormancy (MLD) of *Alangium kurzii* in different moisture contents (normal (NMC) and 5% (5% MC)), storage temperatures (ambient (A) and refrigerator, 5 °C (R)) and storage durations (0, 1, 3 and 6 months), testing in nursery with 3 replicates of 30 seeds, a) Germination and b) MLD.

4.2.2.4 *Bauhinia variegata*

Refrigeration and drying maintained seed viability similar to that of the control, but ambient conditions killed all seeds within 6 months. Mean percent germination of the control was $85.3 \pm 3.7\%$. Germination of refrigerated seeds was not significantly different compared with the control, whereas, 5% MC seeds, stored at ambient temperature germinated significantly less than the control at 12 months' storage ($68.0 \pm 6.9\%$, ANOVA, $p<0.01$, Figure 4.5 a). Mean MLD shortened significantly with increasing storage duration (ANOVA, $p<0.01$, Figure 4.5 b).
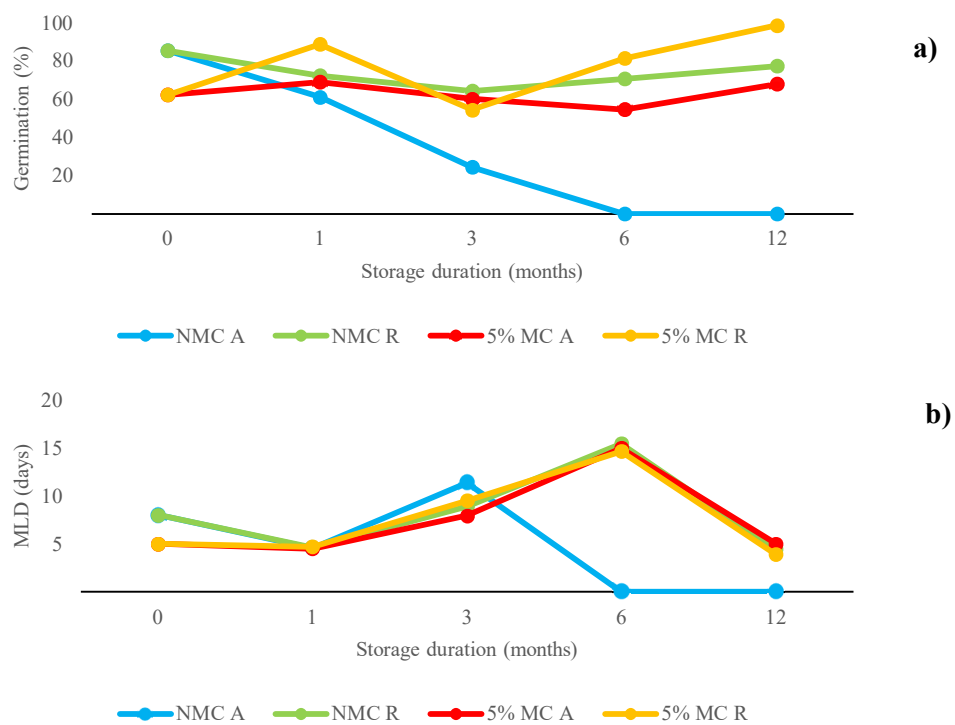
Figure 4.5 Mean percent seed germination and median of dormancy (MLD) of *Bauhinia variegata* in different moisture contents (normal (NMC) and 5% (5% MC)), storage temperatures (ambient (A) and refrigerator, 5 °C (R)) and storage durations (0, 1, 3, 6 and 12 months), testing in nursery with 3 replicates of 30 seeds, a) Germination and b) MLD.

4.2.2.5 *Choerospondias axillaris*

Storage, under all conditions tested, significantly and substantially reduced seed viability (ANOVA, p<0.01, Figure 4.6 a). Mean MLD was also significantly shortened after 12 months' storage (ANOVA, *p<0.01,* Figure 4.6 b).
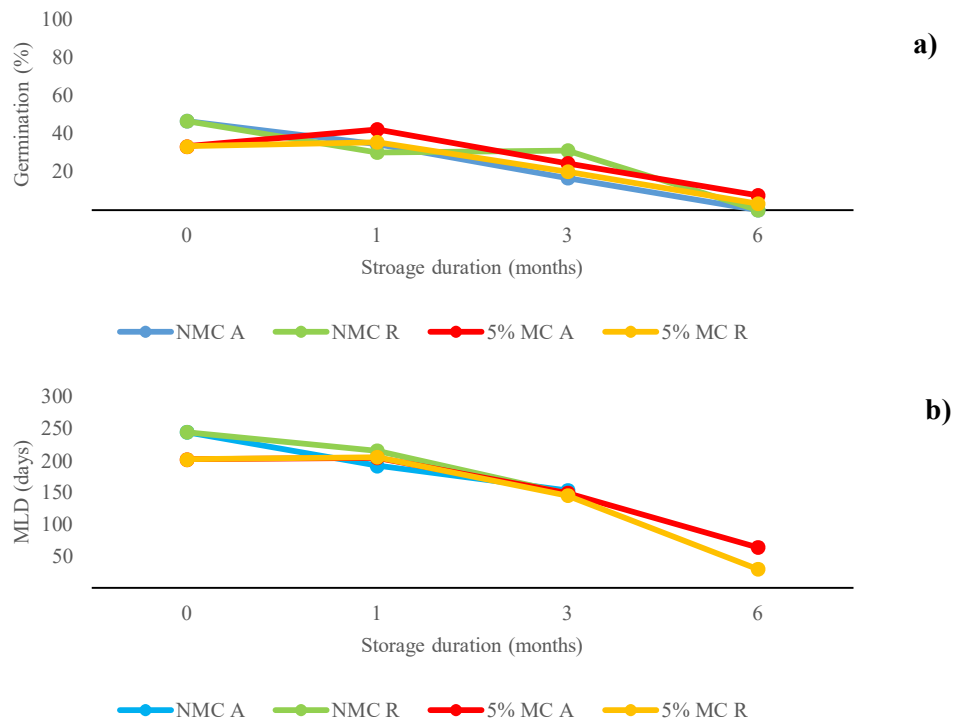
Figure 4.6 Mean percent seed germination and median of dormancy (MLD) of *Choerospondias axillaris,* in different moisture contents (normal (NMC) and 5% (5% MC)), storage temperatures (ambient (A) and refrigerator, 5 °C (R)) and storage durations (0, 1, 3 and 6 months), testing in nursery with 3 replicates of 30 seeds, a) Germination and b) MLD.

4.2.2.6 *Gmelina arborea*

Germination of *G. arborea* seeds was low under all conditions (mostly <10%). Mean percent germination of control was 6.0 ± 1.2 %. Refrigerated seeds at normal MC and dried seeds at both temperatures did not significantly differ in their percent germination compared with the control, although seeds stored under ambient conditions did have the lowest percent germination (ANOVA, $p<0.01$, Figure 4.7 a). Mean MLD of the seeds, subjected to all treatments, did not differ significantly from that of the control after 12 months' storage (ANOVA, $p=0.23$, Figure 4.7 b).
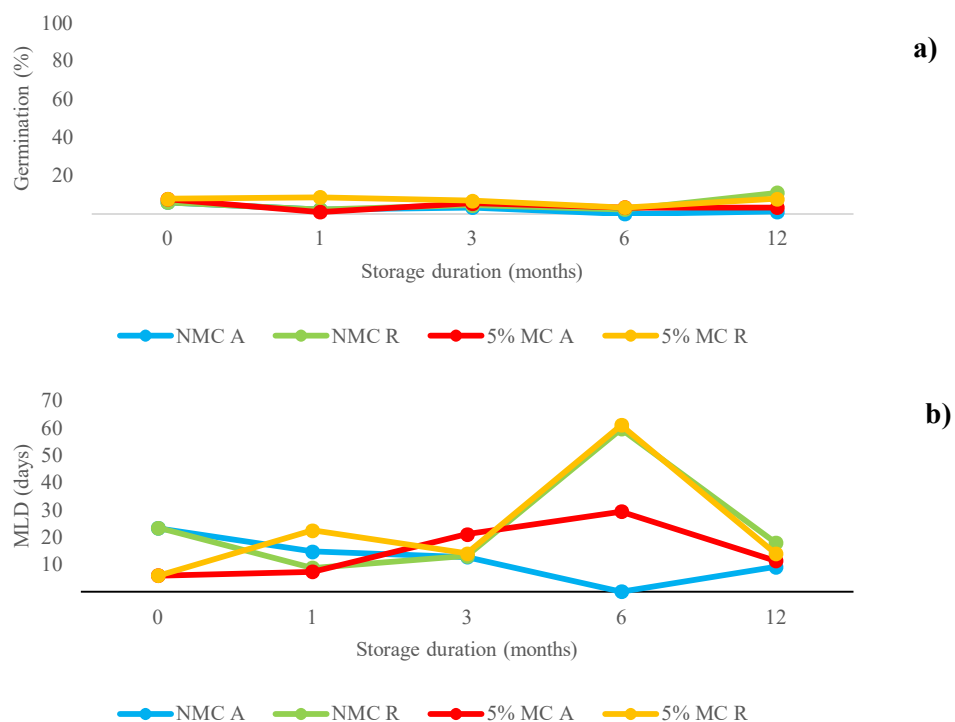
Figure 4.7 Mean percent seed germination and median of dormancy (MLD) of *Gmelina arborea* in different moisture contents (normal (NMC) and 5% (5% MC)), storage temperatures (ambient (A) and refrigerator, 5 °C (R)) and storage durations (0, 1, 3, 6 and 12 months), testing in nursery with 3 replicates of 30 seeds, a) Germination and b) MLD.

4.2.2.7 *Hovenia dulcis*

Storage treatments had no effect on percent germination (ANOVA, *p*=0.26, Figure 4.8a). Mean percent germination of control was 34.7±5.0%. Mean MLD shortened significantly with storage duration, except for seeds stored under ambient conditions (ANOVA, *p*<0.01, Figure 4.8 b).
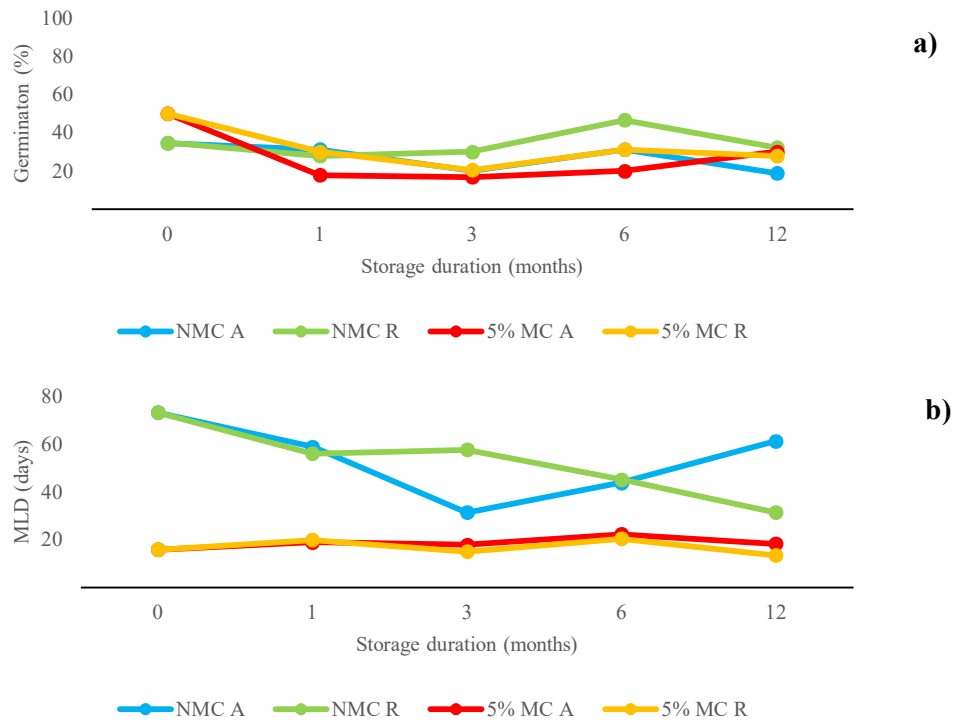
Figure 4.8 Mean percent seed germination and median of dormancy (MLD) of *Hovenia dulcis* in different moisture contents (normal (NMC) and 5% (5% MC)), storage temperatures (ambient (A) and refrigerator, 5 °C (R)) and storage durations (0, 1, 6 and 12 months), testing in nursery with 3 replicates of 30 seeds, a) Germination and b) MLD.

4.2.2.8 *Manglietia garrettii*

Only refrigerated non-dried seeds survived for 12 months. Their viability remained similar to that of the control seeds (*t*-test, *p*=0.59, Figure 4.9 a), but their mean MLD was significantly shortened by 55.5 days (*t*-test, p<0.01, Figure 4.9 b).
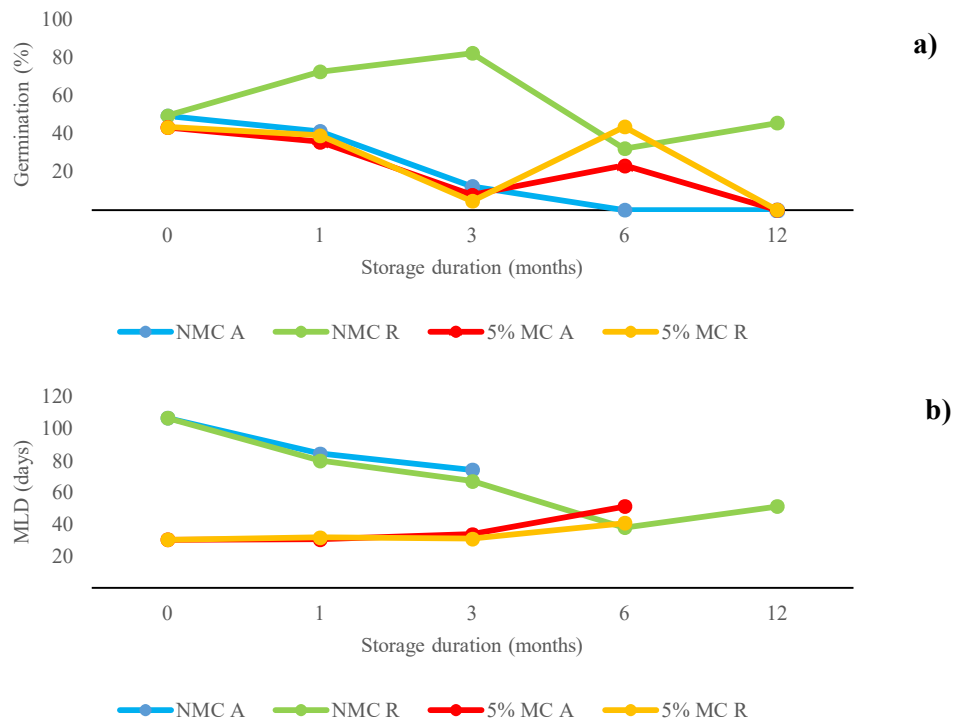
Figure 4.9 Mean (±) percent seed germination and median of dormancy (MLD) of *Manglietia garrettii* in different moisture content (normal (NMC) and 5% (5% MC)), storage temperature (ambient (A) and refrigerator, 5 °C (R)) and storage duration (0, 1, 6 and 12 months), testing in nursery with 3 replicates of 30 seeds, a) Germination and b) MLD.

4.2.2.9 *Melia azedarach*

Whilst germination was fairly low for this species, the treatments produced various results. Mean percent germination of refrigerated normal MC seeds and non-refrigerated dried seeds did not differ with that of the control. However, viability of seeds stored under ambient conditions and refrigerated, dried seeds 5% MC was significantly reduced (ANOVA, $p<0.01$, Figure 4.10 a). Drying significantly reduced mean MLD (ANOVA, $p=0.01$, Figure 4.10 b).
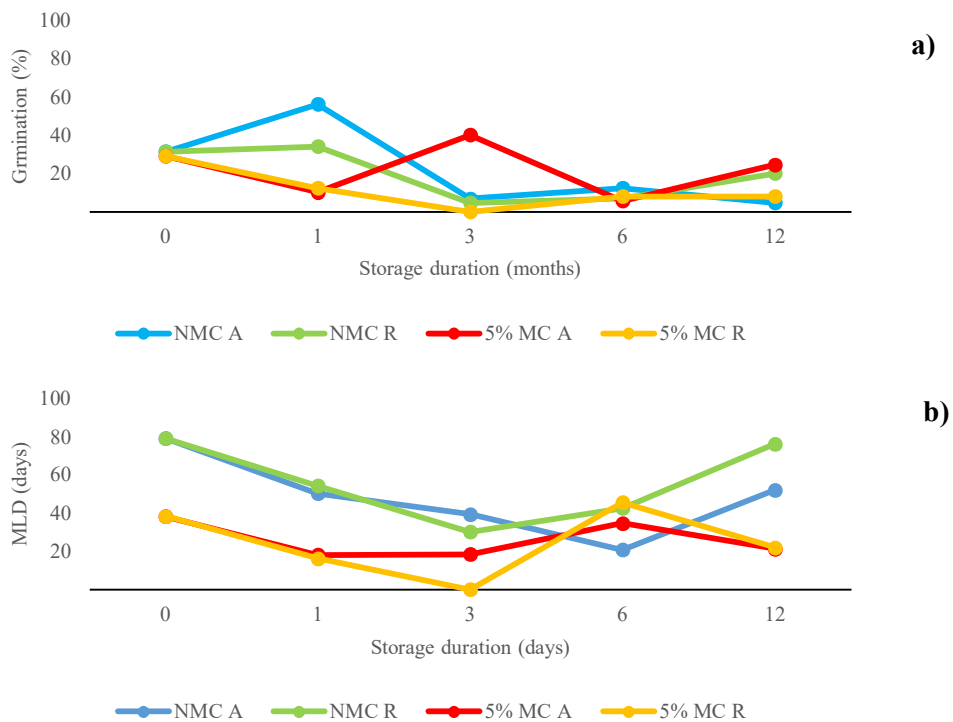
Figure 4.10 Mean ($\pm$) percent seed germination and median of dormancy (MLD) of *Melia azedarach* in different moisture content (normal (NMC) and 5% (5% MC)), storage temperature (ambient (A) and refrigerator, 5 °C (R)) and storage duration (0, 1, 6 and 12 months), testing in nursery with 3 replicates of 30 seeds, a) Germination and b) MLD.

4.2.2.10 *Phyllanthus emblica*

P. emblica seeds also had fairly low germination. Refrigeration killed them, whereas the viability of seeds stored under ambient conditions remained similar to that of the control seeds, although viability declined slightly (but significantly) for dried seeds outside the refrigerator (ANOVA, p=0.05, Figure 4.11 a). In general, mean MLD declined with storage by 93.3 days (for dried seeds at ambient temperature), except for non-dried non-refrigerated seeds whose MLD did not differ significantly from that of the control seeds (ANOVA, $p<0.01$, Figure 4.11 b).
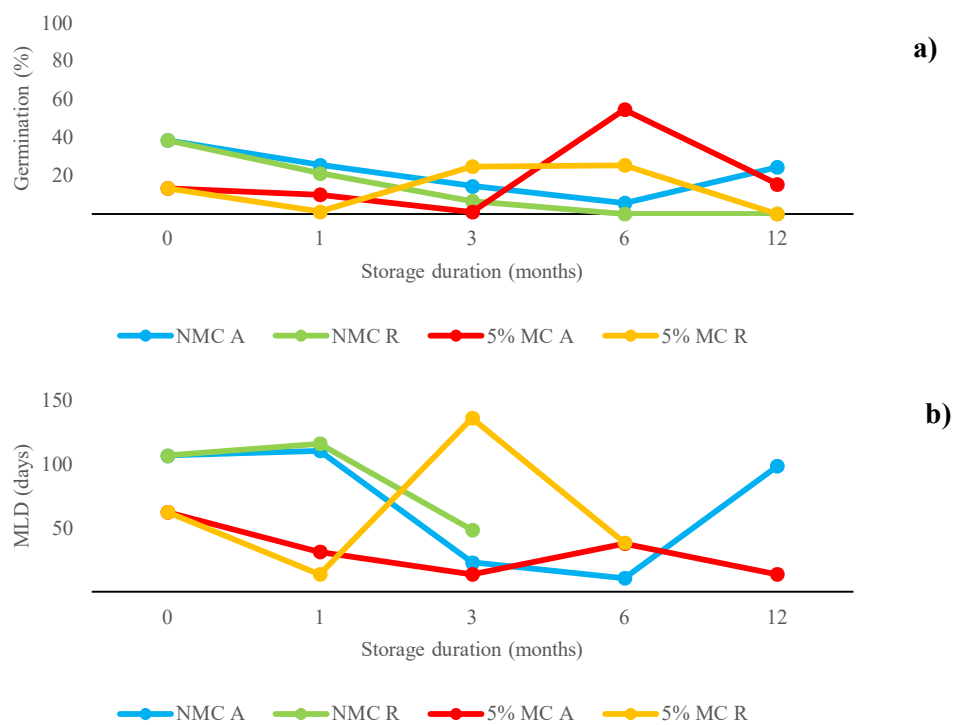
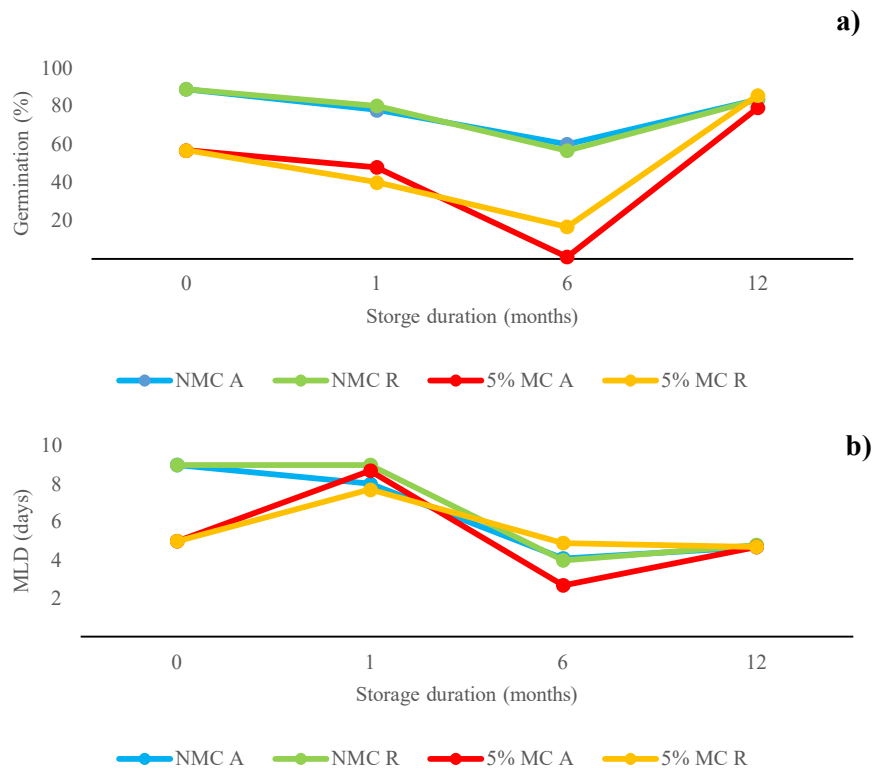**Figure 4.11** Mean (±) percent seed germination and median of dormancy (MLD) of *Phyllanthus emblica* in different moisture content (normal (NMC) and 5% (5% MC)), storage temperature (ambient (A) and refrigerator, 5 °C (R)) and storage duration (0, 1, 6 and 12 months), testing in nursery with 3 replicates of 30 seeds, a) Germination and b) MLD.

4.2.2.11 *Prunus cerasoides*

Under ambient conditions, all seeds were killed within 6 months, but none of the other treatments had any effect on seed viability (ANOVA, *p*=0.13, Figure 4.12 a). All treatments significantly reduced the mean MLD from about 50 to about 10 days. Although mean dormancy also showed no significantly differences between treatments (ANOVA, p=0.11, Figure 4.12 b).
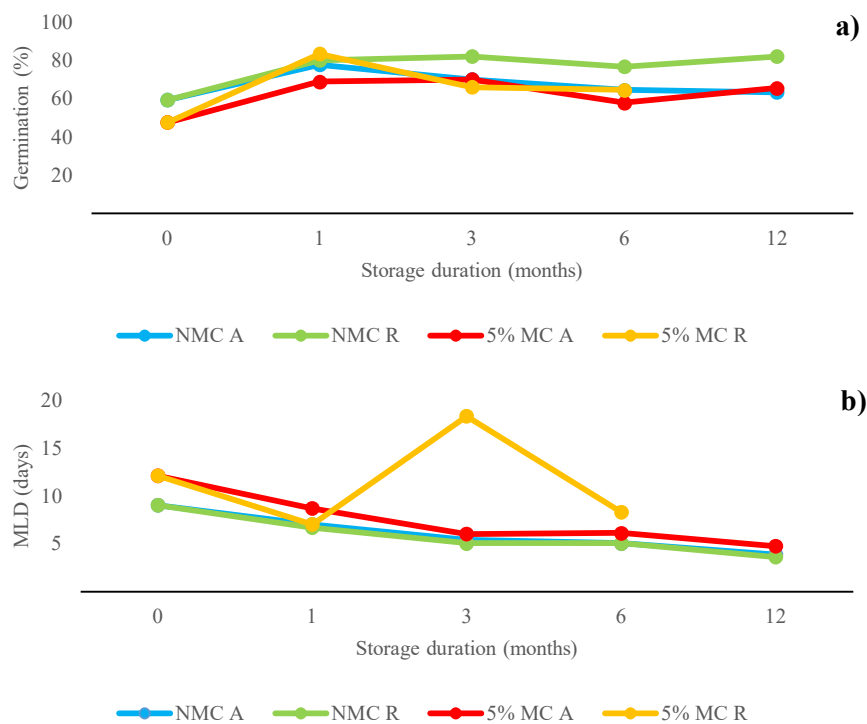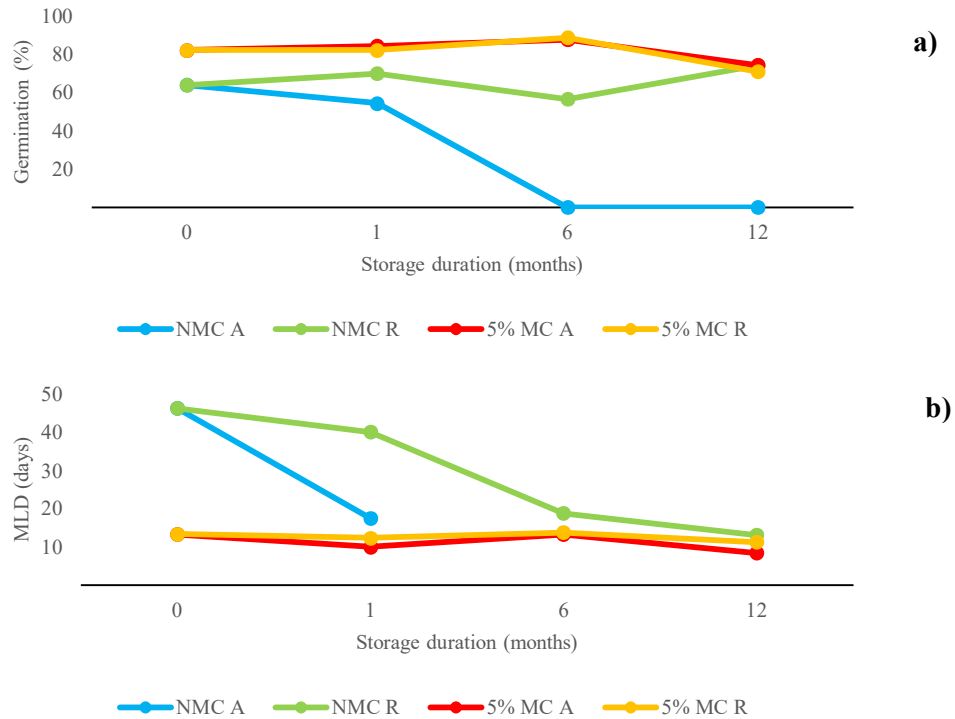

Figure 4.12 Mean (±) percent seed germination and median of dormancy (MLD) of *Prunus cerasoides* in different moisture content (normal (NMC) and 5% (5% MC)), storage temperature (ambient (A) and refrigerator, 5 °C (R)) and storage duration (0, 1, 6 and 12 months), testing in nursery with 3 replicates of 30 seeds, a) Germination and b) MLD.

4.2.2.12 *Spondias pinnata*

Germination was low and refrigeration had no effect on both seed viability (test at different times, ANOVA, p=0.23, Figure 4.13 a) and mean MLD (ANOVA, p=0.32, Figure 4.13 b).
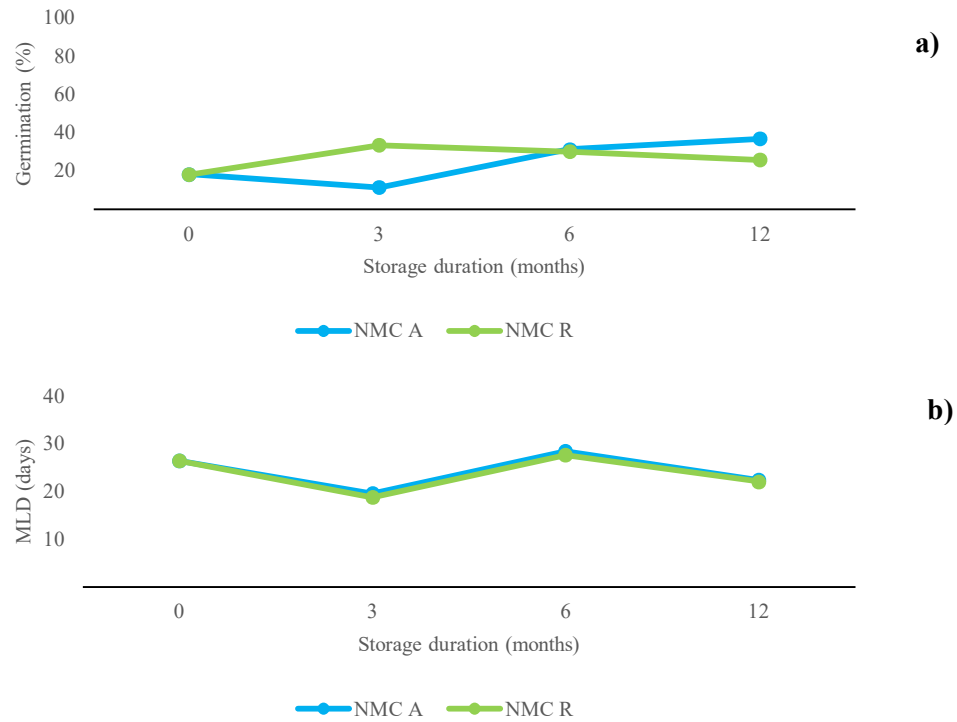
Figure 4.13 Mean (±) percent seed germination and median of dormancy (MLD) of *Spondias pinnata* in different storage temperature (ambient (A) and refrigerator, 5 °C (R)) and storage duration (0, 1, 6 and 12 months), testing in nursery with 3 replicates of 30 seeds, a) Germination and b) MLD.

4.3 Field Trials

4.3.1 Seed Germination

D. longan was the first species sown in the field (October 2014) and *A. kurzii* and *C. axillaris* were the last (July 2015). Two analyses were carried out: i) to compare seed germination at collection time in the nursery (optimal conditions) and field (natural conditions) and ii) to compare between two sowing times: immediately after collection and at the beginning of the rainy season after storage since collection.

Comparing immediate sowing at collection time, between nursery experiments (Immediately sown in Nursery, IN) and field trials (Immediately sown in Field, IF), percent germination did not differ significantly between the nursery and field for all species except three: *A. fraxinifolius, A. lacucha* and *C. axillaris* germinated significantly better in the nursery (IN>IF by 42%, 32% and 25%, respectively, *t*-test, $p < 0.05$, Figure 4.14).
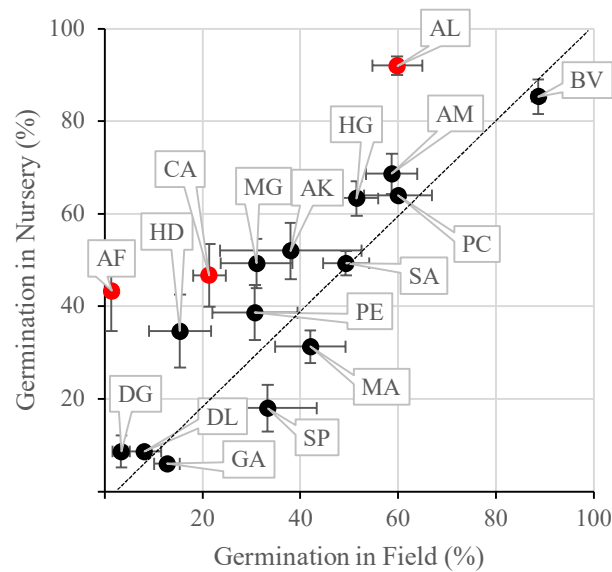
Figure 4.14 Comparison of mean (± SE) percent seed germination of 17 tree species, seeds sown at collection time, in the field (IF) and in the nursery (IN), 3 replicates of 50 seeds. Red circles indicate significant difference between the two bars within each species (t-test, p < 0.05). Dashed line indicates axis X equals axis Y. AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea*, HG=*H. glabra*, HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii*, PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

Similarly, after storage, mean percent germination at the beginning of rainy season did not differ significantly between nursery experiments (Stored seeds sown in the Nursery, SN) and field trials (Stored seeds sown in the Field, SF) for all species except three: *M. azedarach, M. garrettii* and *P. emblica* germinated significantly better in the field than in the nursery (SF>SN by 36%, 16% and 25%, respectively, *t*-test, *p*<0.05, Figure 4.15).
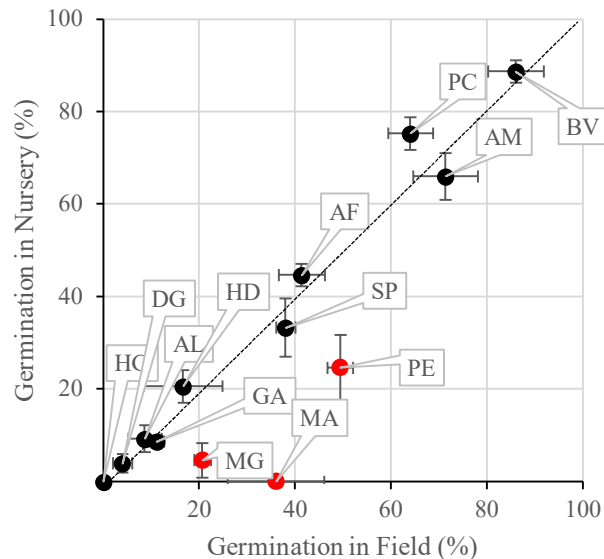
Figure 4.15 Comparison of mean (± SE) percent seed germination of 13 tree species between two sowing conditions after seed storage, in the field (SF) and in the nursery (SN), 3 replicates of 50 seeds. Red circles indicate significant difference between the two bars within each species (t-test, p < 0.05). Dashed line indicates axis X equals axis Y. AF=*A. fraxinifolius*, AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea*, HG=*H. glabra*, HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii*, PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

Comparing between the two sowing times (immediate and after storage) in field trials, one species, *H. glabra,* germinated only when sown immediately at collecting time (51.4 ± 4.4 %, Figure 4.16). Similarly, immediately sown *A. lacucha* seeds germinated far more (51 % significantly higher) than stored seeds, even though the seeds were stored for only 11 days (*t*-test, *p*<0.01, Figure 4.16). In contrast, *A. fraxinifolius* was the only species with percent germination of seeds sown after storage significantly higher (by 40 %) than for those sown at collection time (*t*-test, *p*<0.01, Figure 4.16).
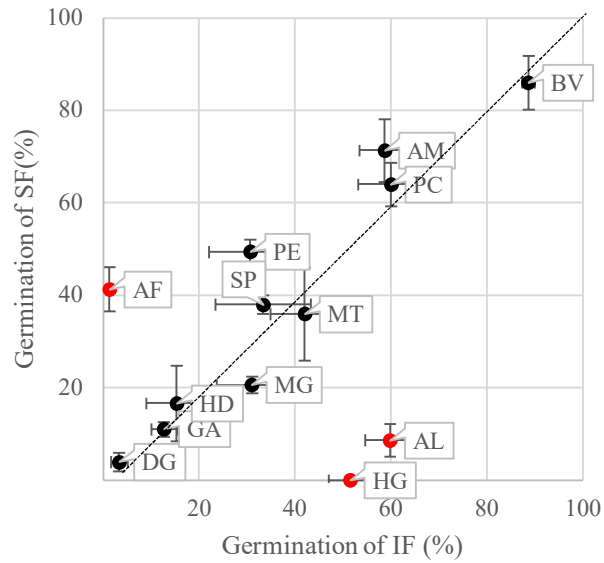
Figure 4.16 Comparison of mean (± SE) percent seed germination of 13 tree species between two sowing times in the field condition, at collection time (IF) and at the beginning of rainy season after storage (SF), 3 replicates of 50 seeds. *A. microsperma* and *A. fraxinifolius* seeds were scarified in SF treatment. Red circles indicate significant difference between the two bars within each species (t-test, p < 0.05). Dashed line indicates axis X equals axis Y. AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii*, AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra,* HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii*, PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

Seeds of *D. longan* and *S. albiflorum* became desiccated and lost viability rapidly after seed collection and the seeds of *A. kurzii* and *C. axillaris* were collected during the rainy season, so germination tests on these species were performed only on seeds sown at collecting time.

61

Considering the most effective treatment for each species, the mean (± SE) percent seed germination was compared across species to rank them according to germination, as a major component of suitability for direct or aerial seeding. *B. variegata* exhibited the highest percent germination (88.7 ± 1.3 %), from immediate sowing at collection time (IF), followed by stored seeds of *A. microsperma* and *P. cerasoides* sown at the start of the rainy season (71.3.0 ± 6.8 % and 64.0 ± 4.7 %, respectively). In contrast, *D. glandulosa* (SF) germinated the least (only 4.0 ± 2.0 %,). A similar result was obtained with *D. longan* (IF) (only 8.1 ± 3.5 %, Figure 4.17).
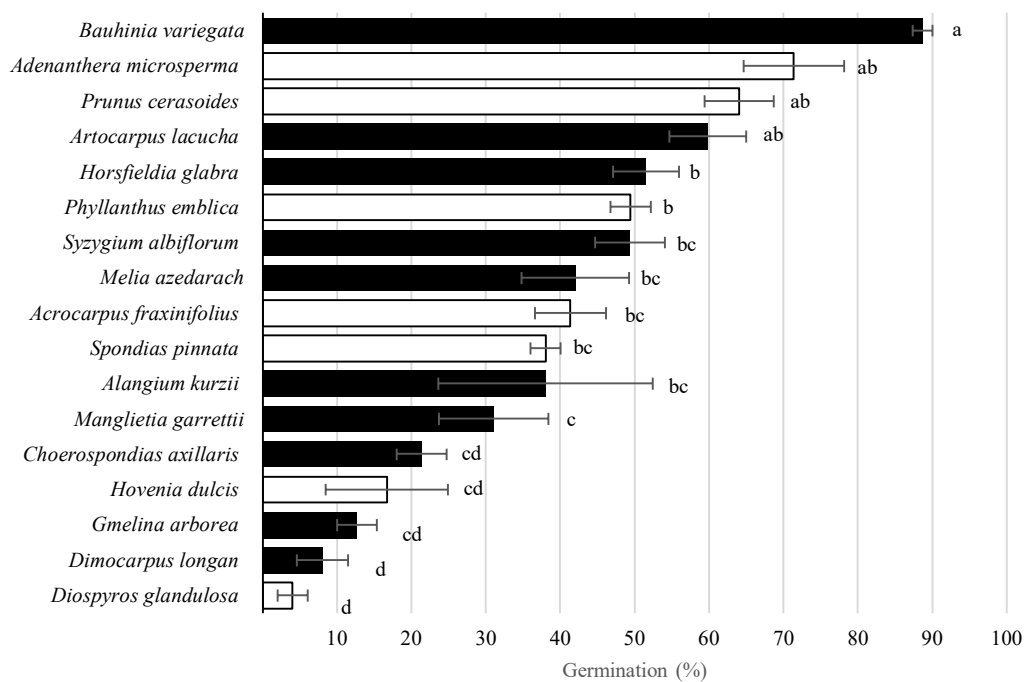
Figure 4.17 Mean (± SE) percent seed germination of the best performance treatment of each tree species in the field. Black bars are treatment of seed sown at collection times and white bars are treatment of seed sown at beginning of rainy season after storage (N=3). Bars not sharing the same superscript letters are statistically different among species (mean differentiation using Turkey's HSD, α= 0.05).

4.3.2 Median Length of Dormancy (MLD)

Mean dormancy was compared between seeds sown in the nursery and field at seed collection time (IN & IF). Six species took significantly longer to germinate in the field than in the nursery; *A. lacucha* (IF>IN 22 days, *t*-test, *p*=0.01), *A. microsperma* (IF>IN 50 days, *t*-test, *p*<0.01), *H. glabra* (IF>IN 26 days, *t*-test, *p*=0.02), *M. azedarach* (IF>IN 38 days, *t*-test, *p*<0.01), *S. pinnata* (IF>IN 79 days, *t*-test, *p*<0.01) and *S. albiflorum* (IF>IN 10 days, *t*-test, *p*=0.01). Three species exhibited the opposite result; *A. fraxinifolious* (IF<IN 90 days, *t*-test, *p*=0.04), *B. variegata* (IF<IN 5 days, *t*-test, *p*<0.01) and *C. axillaris* (IF<IN 157 days, *t*-test, *p*<0.01, Figure 4.18).
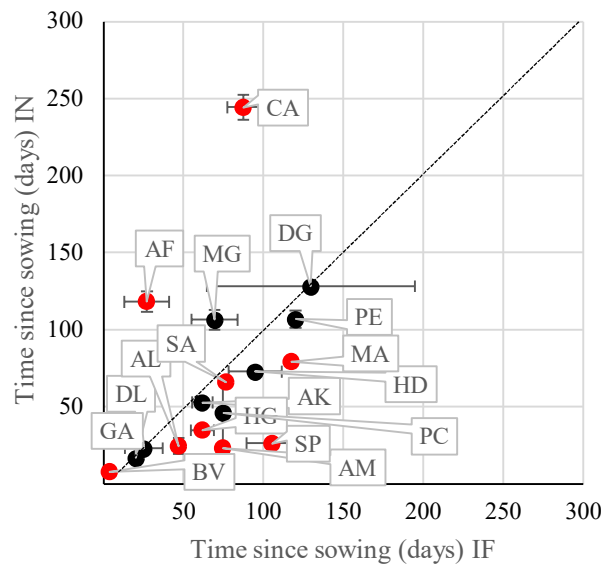
Figure 4.18 Comparison of mean (± SE) MLD's of 17 tree species, seeds sown at collection time, in the field (IF) and in the nursery (IN) (N=3). Red circles indicate significant difference between the two bars within each species (t-test, p < 0.05). Dashed line indicates axis X equals axis Y. AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii*, PE=*P. emblica*, PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

Comparing MLD after seed storage between the nursery experiments and the field trials, 5 species had longer mean MLD in the field than in the nursery; *A. microsperma* (SF>SN 10 days, *t*-test, *p*<0.01), *B. variegata* (SF>SN 3 days, *t*-test, *p*=0.01), *M. azedarach* (SF>SN 20 days, *t*-test, *p*<0.01), *P. cerasoides* (SF>SN 3 days, *t*-test, *p*=0.01) and *S. pinnata* (SF>SN 10 days, *t*-test, *p*<0.01, Figure 4.19).
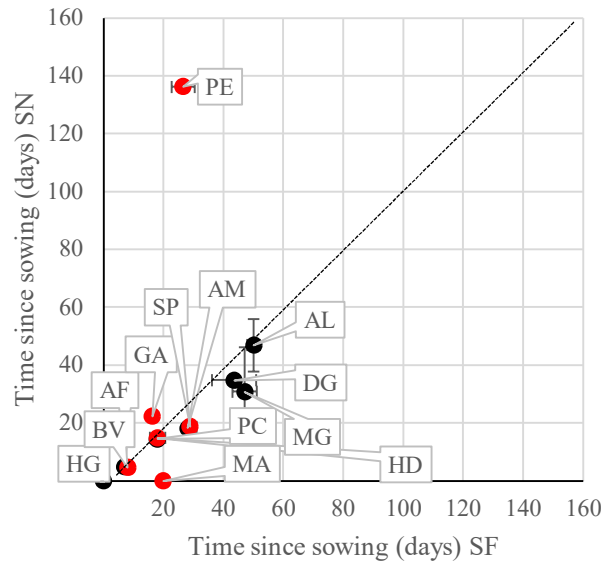
Figure 4.19 Comparison of mean (± SE) MLD's of 13 tree species between two sowing conditions after seed storage, in the field (SF) and in the nursery (SN), (N=3). Red circles indicate significant difference between the two bars within each species (t-test, p < 0.05). Dashed line indicates axis X equals axis Y. AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii*, PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

In the field, seeds of most species, sown at collection time (IF), had significantly longer MLD than those stored and sown at beginning of rainy season (SF): *A. microsperma* (IF > SF 46 days, seeds stored 112 days, *t*-test, *p*<0.01), *H. glabra* (IF > SF 61.8 days, seeds stored 24 days, *t*-test, *p*<0.01), *H. dulcis* (IF > SF 78 days, seeds stored 112 days, *t*-test, *p*=0.01), *M. azedarach* (IF > SF 97 days, seeds stored 159 days, *t*-test, *p*<0.01), *P. emblica* (IF > SF 93 days, seeds stored 166 days, *t*-test, *p*<0.01) *P. cerasoides* (IF > SF 57 days, seeds stored 62 days, *t*-test, *p*<0.01) and *S. pinnata* (IF > SF 76 days, seeds stored 79 days, *t*-test, *p*<0.01, Figure 4.20).

B. variegata seeds were the only ones with significantly longer dormancy when stored and sown at the start of the rainy season (SF, 28 days' storage), compared with IF, but the difference was only 4 days (*t*-test, *p*<0.01, Figure 4.20).
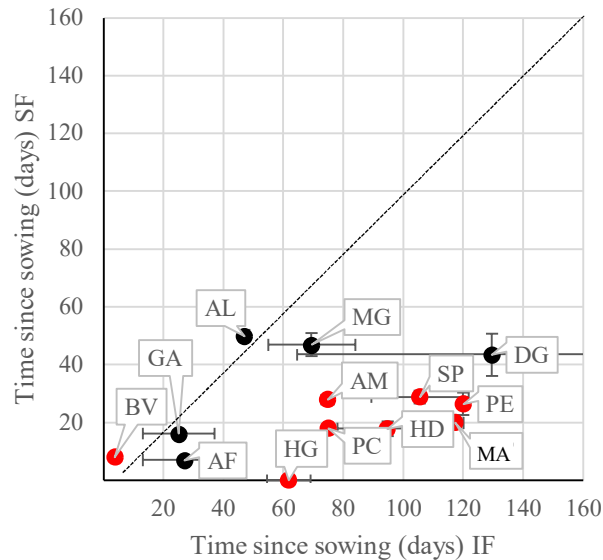
Figure 4.20 Comparison of mean (± SE) median length of dormancy of 13 tree species between two sowing times in the field condition, at collection time (IF) and at the beginning of rainy season after storage (SF), (N=3). Red circles indicate significant difference between the two bars within each species (t-test, p < 0.05). Dashed line indicates axis X equals axis Y. AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan*, DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii*, PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

For seeds sown in the field at collection time (IF), most seeds germinated just before the start of the rainy season (using median date of germination). The exceptions were *D. longan*, *D. glandulosa* and *M. garrettii* whose median germination dates fell in October, December and March respectively (Table 4.5 and Figure 4.21a). For seeds sown after storage (sowing date 12/06/16), all species had median germination dates within the rainy season (June to August 2015, Table 4.5 and Figure 4.21 b).
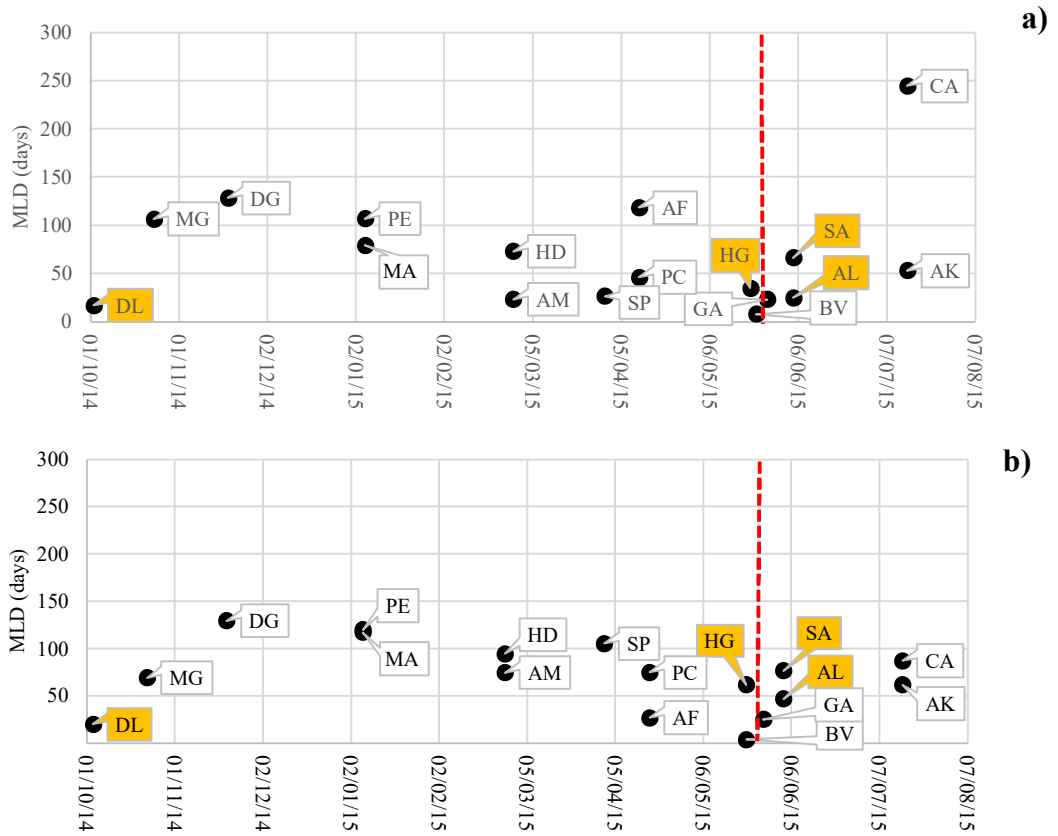
Figure 4.21 Sowing date and median length of dormancy (MLD) of 17 tree species in a) nursery and b) field. Red line is a starting point of rainy season (22 May 2015). Orange boxes are recalcitrant species and white are orthodox. AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan, DG=D. glandulosa*, GA=*G. arborea,* HG=*H. glabra,* HD=*H. dulcis,* MG=*M. garrettii*, MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

Table 4.5 Sowing, median length of dormancy (MLD) and median date of germination of 17 tree species in two sowing condition; sown at collection time (IF) and sown after storage at the beginning of rainy season (SF). Species were ordered from sowing date in IF.

Species	IF			SF		
	Sowing date	MLD (days)	Median date of germination	Sowing date	MLD (days)	Median date of germination
Dimocarpus longan	03/10/14	20.2	23/10/14	-	-	-
Manglietia garrettii	22/10/14	69.3	30/12/14	12/06/15	47.0	29/07/15
Diospyros glandulosa	19/11/14	129.5	28/03/15	12/06/15	43.5	25/07/15
Melia azedarach	06/01/15	117.3	03/05/15	12/06/15	20.0	01/07/15
Phyllanthus emblica	06/01/15	120.0	05/05/15	12/06/15	26.5	08/07/15
Adenanthera microsperma	25/02/15	74.7	10/05/15	12/06/15	28.0	10/07/15
Hovenia dulcis	25/02/15	94.7	30/05/15	12/06/15	17.9	29/06/15
Spondias pinnata	01/04/15	105.4	15/07/15	12/06/15	28.9	10/07/15
Acrocarpus fraxinifolius	17/04/15	27.0	14/05/15	12/06/15	7.0	19/06/15
Prunus cerasoides	17/04/15	74.9	30/06/15	12/06/15	17.9	29/06/15
Bauhinia variegata	21/05/15	3.8	24/05/15	12/06/15	8.0	20/06/15
Horsfieldia glabra	21/05/15	61.8	21/07/15	12/06/15	-	-
Gmelina arborea	27/05/15	25.1	21/06/15	12/06/15	16.2	28/06/15
Artocarpus lacucha	03/06/15	46.9	19/07/15	12/06/15	50.0	01/08/15
Syzygium albiflorum	03/06/15	76.5	18/08/15	-	-	-
Alangium kurzii	15/07/15	61.7	14/09/15	-	-	-
Choerospondias axillaris	15/07/15	87.3	10/10/15	-	-	-

Regression analysis showed no significant correlation between MLD and percent germination, neither for seeds sown at collection time (r=0.19, *p*=0.46, N=17, Figure 4.22 a) nor for seeds sown after storage (r=0.54, *p*=0.07, N= 12, Figure 4.22 b). A similar trend was detected when combining data from the two treatments and applying the same analysis (r=0.17, *p*=0.50, N= 17, Figure 4.22 c).
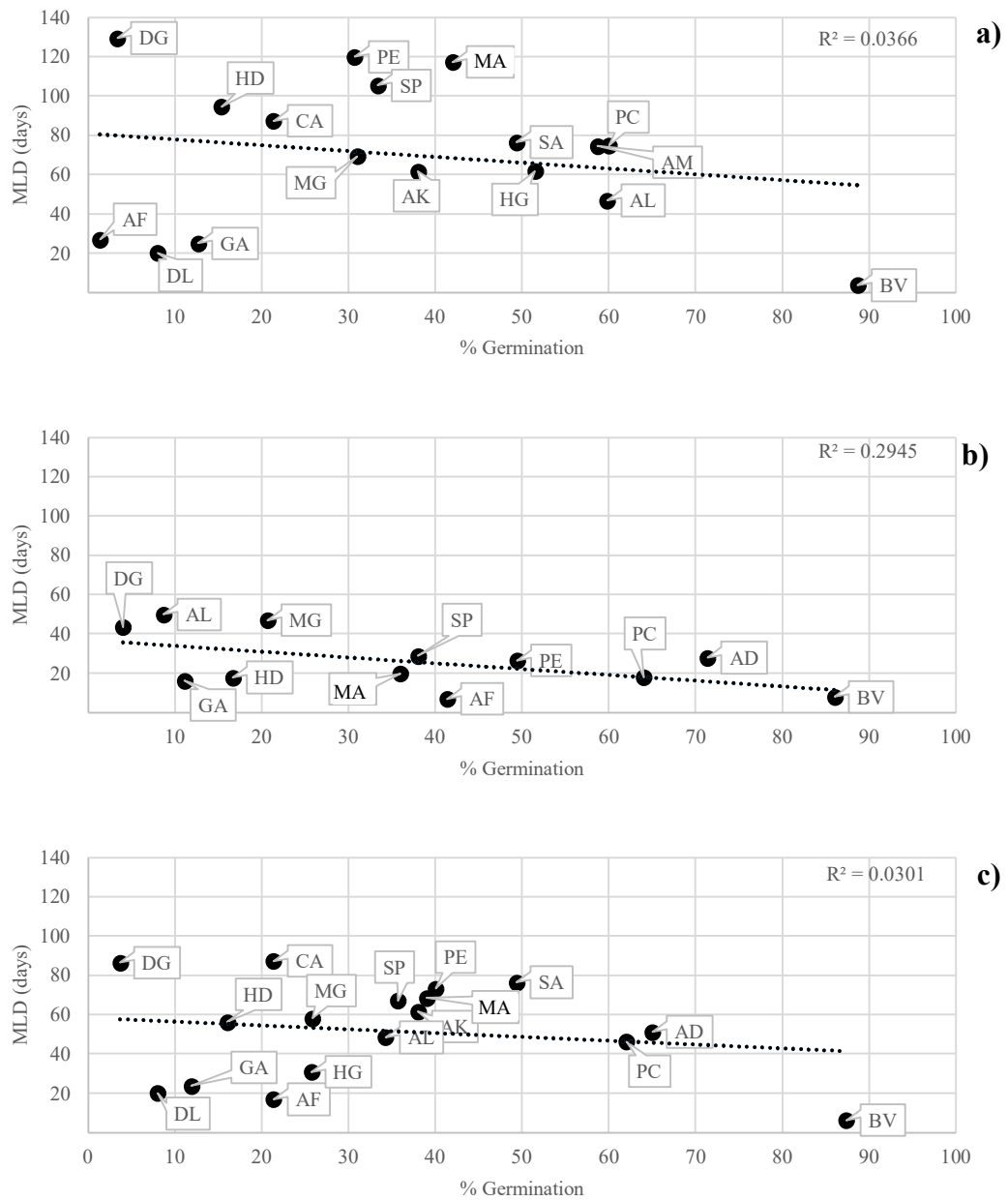
Figure 4.22 Relationships between mean percent seed germination and median length of dormancy (MLD) of 17 tree species in the field at two sowing times; a) collection time (N=17) b) at the beginning of rainy season after storage (N=12) c) combining the two periods (N=17). The dotted line is the line of best fit. AF=*A. fraxinifolius,* AM=*A. microsperma,* AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa,* GA=*G. arborea,* HG=*H. glabra,* HD=*H. dulcis,* MG=*M. garrettii,* MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

4.3.3 Seedling Survival and Seedling Yield

Seedling survival was defined as the number of surviving seedlings, expressed as a percentage of the seeds that germinated after 12 months. *B. variegata* achieved the highest percent survival (69.7 ± 9.1 %), followed by *P. emblica* (51.1 ± 10.2 %). *A. fraxinifolius*, *G. arborea* and *H. dulcis* had low survival percentages in the field (1.1 ± 1.1 %, 3.3 ± 2.2 % and 3.3 ± 3.3 %, respectively, Figure 4.23). In general, percent survival was not significantly different between the two sowing periods.

A. fraxinifolius seedlings from immediate sowing did not survive, while all of *G. arborea* seedlings from seed stored treatment died in the field (Table 4.6). These two species presented low percent seedling survival when compared with the other species (Figure 4.23).
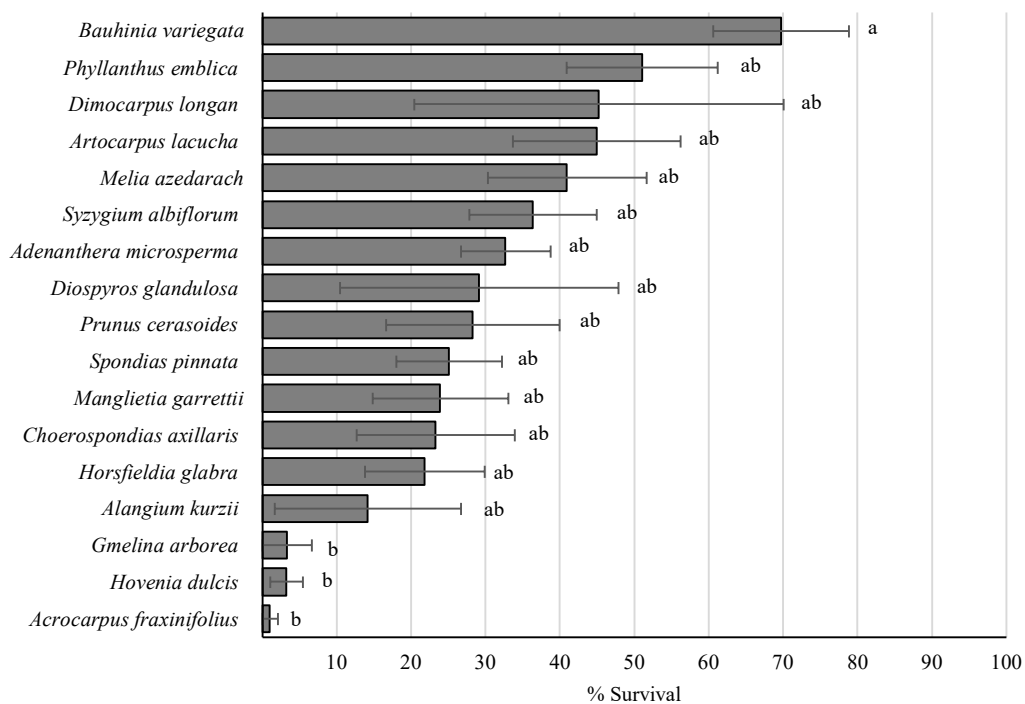
Figure 4.23 Comparison of mean (± SE) seedling survival, over one year, of direct-seeded seedlings in the field, calculated as a percent of the number of seeds that germinated, using combined data from two seed sowing times, collection time and beginning of rainy season after storage (N=6). Columns not sharing the same superscript letters are statistically different, among species (mean differentiation using Turkey's HSD, α= 0.05).

69

Table 4.6 Comparison of mean seedling survival, over one year, of direct-seeded seedlings of 17 tree species in the field, at two sowing periods, IF = sown at collection time and SF = seeds stored and sown at the beginning of rainy season (N=3). The t-tests indicated no significant differences between the 2 sowing times. Therefore, data were pooled for Figure 4.23.

Species	Storage duration (days)	IF		SF		t-test, p-value
		Mean	SE	Mean	SE	
Bauhinia variegata	28	67.1	16.9	72.3	11.2	0.83
Phyllanthus emblica	166	46.6	16.7	55.6	14.7	0.70
Dimocarpus longan	-	45.2	24.9	-	-	-
Artocarpus lacucha	11	44.2	8.4	45.7	23.8	0.85
Syzygium albiflorum	-	36.4	8.6	-	-	-
Diospyros glandulosa	209	33.3	33.3	25.0	25.0	0.79
Melia azedarach	159	32.4	11.6	49.5	18.9	0.51
Adenanthera microsperma	112	25.1	5.6	40.3	9.6	0.24
Spondias pinnata	79	24.9	12.5	25.3	9.7	0.81
Prunus cerasoides	62	23.9	19.9	32.7	16.3	0.60
Choerospondias axillaris	-	23.3	10.6	-	-	-
Horsfieldia glabra	24	21.8	8.1	-	-	-
Manglietia garrettii	236	19.5	9.8	28.3	17.4	0.79
Alangium kurzii	-	14.2	12.5	-	-	-
Gmelina arborea	22	6.7	6.7	0.0	0.0	0.42
Hovenia dulcis	112	2.4	2.4	4.2	4.2	0.85
Acrocarpus fraxinifolius	62	0.0	0.0	2.1	2.1	0.42

Seedling yield was defined as the number of seedlings that survived to reach 1-year-old, expressed as a percent of the number of seeds sown. *B. variegata* achieved the highest yield in the field (60.7 ± 8.7 %). Species mostly presented low percent yield of less than 20 percent. *A. fraxinifolius* and *H. dulcis* had lowest yield: only 0.3 ± 0.3 % (Figure 4.24). Percent yield of most species were not significant different between two sowing periods. All *A. fraxinifolius* seedlings from immediate sowing died in the field (Table 4.7). *A. lacucha* was the only species, for which percent yield from immediately sown seeds was significant higher (22 %) than for those from stored seeds (*t*-test, *p*=0.04, Table 4.7).
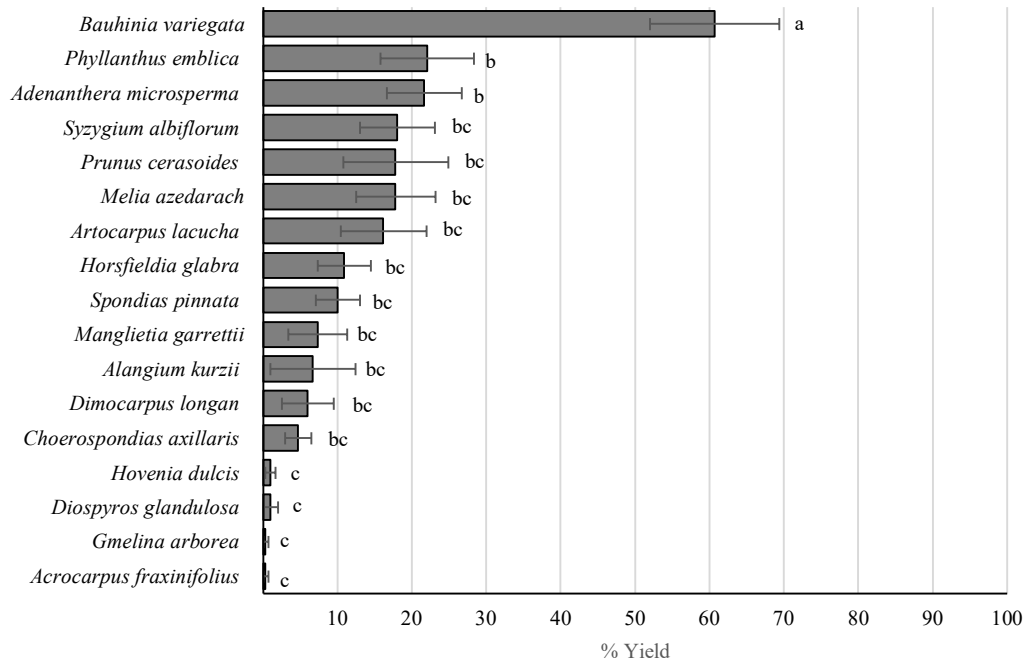
Figure 4.24 Comparison of mean (± SE) percent seedling yield over one year of direct-seeded seedlings in the field, calculated from two seed sowing times, at collection time and beginning of rainy season after storage (N=6). Columns not sharing the same superscript letters are statistically different among species (mean differentiation using Turkey's HSD, α= 0.05).

Table 4.7 Seedling yield, over one year, of direct-seeded seedlings of 17 tree species in the field at two sowing periods, IF = sown at collection time and SF = seeds stored and sown at the beginning of rainy season (N=3). T-tests indicated no difference between IF and SF. Therefore, data were pooled for Figure 4.24.

Species	Storage duration (days)	IF		SF		t-test, p-value
		Mean	SE	Mean	SE	
Bauhinia variegata	28	57.3	13.7	64.0	13.3	0.72
Artocarpus lacucha	11	27.0*	6.4	5.3	2.7	0.04
Syzygium albiflorum	-	18.0	5.0	-	-	-
Phyllanthus emblica	166	17.3	10.5	26.8	8.1	0.46
Adenanthera microsperma	112	15.3	4.7	28.0	8.1	0.23
Prunus cerasoides	62	14.7	11.8	20.9	10.0	0.56
Melia azedarach	159	14.0	5.0	21.6	10.2	0.67
Horsfieldia glabra	24	10.9	3.6	-	-	-
Manglietia garrettii	236	10.7	7.9	4.0	2.0	0.61
Spondias pinnata	79	10.0	5.3	10.0	4.0	0.86
Alangium kurzii	-	6.7	5.7	-	-	-
Dimocarpus longan	-	6.0	3.5	-	-	-
Choerospondias axillaris	-	4.7	1.8	-	-	-
Gmelina arborea	22	0.7	0.7	0.0	0.0	0.42
Hovenia dulcis	112	0.7	0.7	1.3	1.3	0.82
Acrocarpus fraxinifolius	62	0.0	0.0	0.7	0.7	0.42
Diospyros glandulosa	209	0.0	0.0	2.0	2.0	0.42

Asterisk (*) indicates statistical difference among treatments ($p < 0.05$)

4.2.4 Seedling Growth Performance

Differences in height, crown width (CW) and root collar diameter (RCD) of 1-year-old seedlings, between those grown from immediately sown seeds and those grown from stored seeds were not significant within species (Figure 4.25) and sowing periods (*t*-tests, height, $p=0.85$, CW, $p=0.78$ & RCD, $p=0.92$, Table 4.8). *P. cerasoides* seedlings grew the tallest (87.4 ± 22.1 cm), followed by *M. azedarach* (46.9 ± 13.4 cm) and *B. variegata* (30.4 ± 2.7 cm). The remaining species grew to less than 30 cm tall. *A. fraxinifolius* seedlings were the smallest, only 4.3 ± 4.3 cm tall (Figure 4.26 a).

A similar pattern was found with crown width. *P. cerasoides* achieved the greatest mean crown expansion (47.9 ± 12.2 cm), followed by *M. azedarach* (31.7 ± 8.8 cm) and *B. variegata* (19.6 ± 1.8 cm). *A. fraxinifolius* seedlings had the smallest crowns (3.3 ± 3.3 cm) (Figure 4.26 b).

P. cerasoides achieved the widest stems after 1 year (RCD, 6.5 ± 1.5 mm) followed by *M. azedarach* (5.9 ± 1.0 mm), whilst of *A. fraxinifolius* and *H. dulcis* were less than 1 mm (0.6 ± 0.6 mm and 0.7 ± 0.5 mm, respectively, Figure 4.26 c).

Table 4.8 Comparison of mean size variables (height, crown width and root collar diameter) and relative growth rate (RGR) of one year direct-seeded seedlings across 17 species in the field, between two sowing periods, IF=sown at collection time, SF= seeds stored and sown at the beginning of rainy season (N=3).

Variables	IF		SF		*t*-test, *p-value*
	Mean	SE	Mean	SE	
Height (cm)	19.4	3.8	20.6	4.6	0.85
Crown width (cm)	13.6	2.4	14.7	2.7	0.78
Root collar diameter (mm)	2.7	0.4	2.7	0.4	0.92
Height RGR (%/year)	57.8	8.2	54.8	10.9	0.83
Crown width RGR (%/year)	46.6	9.6	36.1	10.9	0.48
Root collar diameter RGR (%/year)	58.8	8.9	57.4	9.5	0.92
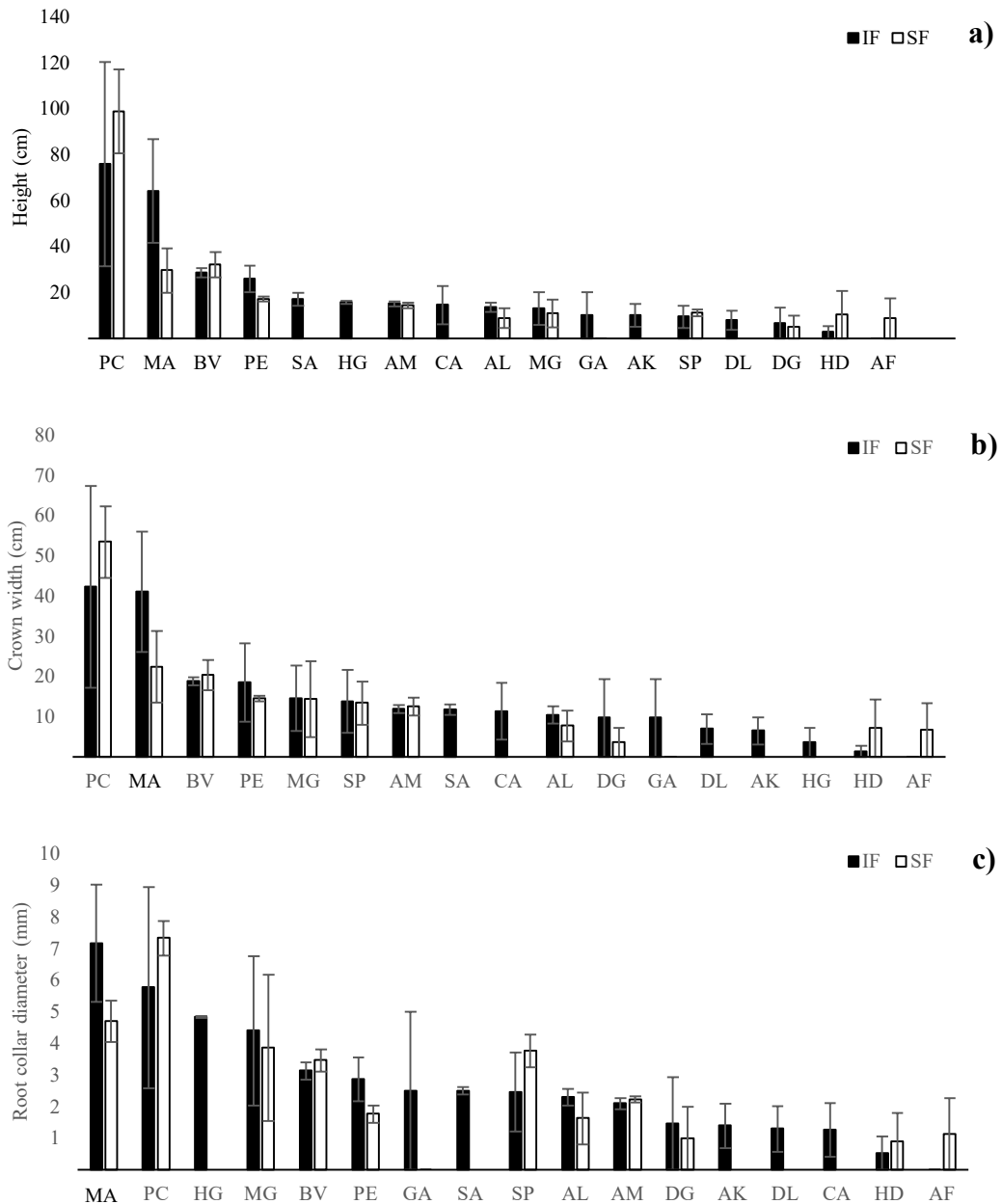
Figure 4.25 Comparison of mean (± SE) growth variables of 1 year direct-seeded seedlings of 17 tree species in the field between two sowing periods, IF = sown at collection time, SF=Stored and sown at the beginning of rainy season (N=3). a) Height, b) Crown width and c) Root collar diameter. Species; AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MG=*M. garrettii*, MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*
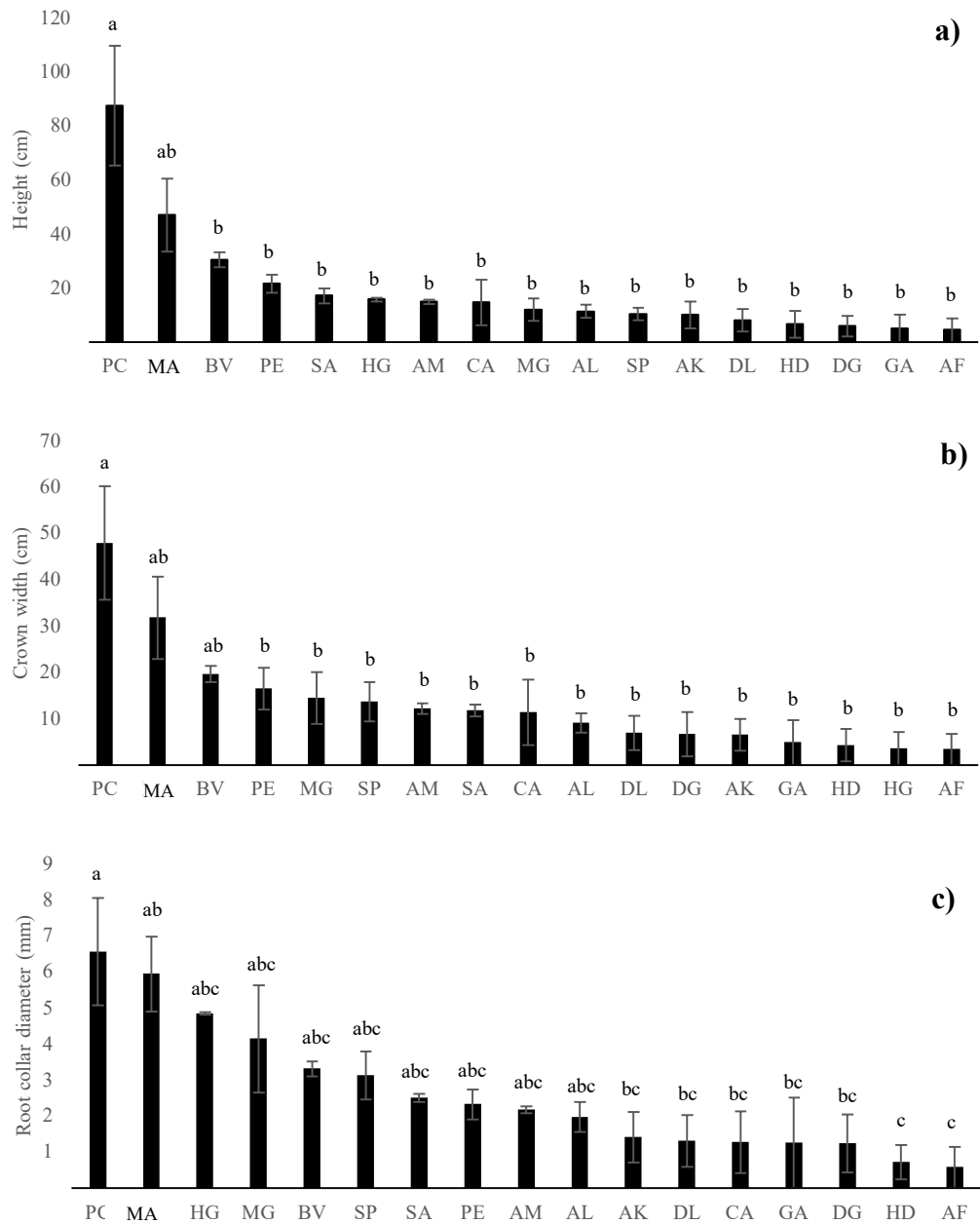
Figure 4.26 Comparison of mean (± SE) seedlings performance of 1 year direct-seeded seedlings in the field, calculated from two seed sowing times, at collection time and beginning of rainy season after storage, N=6. a) Height, b) M Crown width c) Root collar diameter. Species; AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MG=*M. garrettii*, MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.* Columns not sharing the same superscript letter are significantly different (Turkey's HSD, α= 0.05).

Differences in relative growth rate (RGR) of 1-year-old seedlings, compared between the two sowing periods, were not significant (*t*-test, height RGR, *p*=0.83, Crown width RGR, *p*=0.48 and RCD RGR, *p*=0.92, Table 4.9) across all species and at the individual species level (Figure 4.27). *P. cerasoides* seedlings grew the fastest (height RGR (171.7 ± 37.9 %/year), followed by *M. azedarach* (127.3 ± 27.9 %/year). Conversely, *G. arborea, S. pinnata* and *H. dulcis* grew the slowest, with height RGR values of 15.6 ± 15.6, 17.6 ± 12.1 and 17.7 ± 17.7 %/year, respectively, Figure 4.28 a).

P. cerasoides also achieved the highest rate of crown expansion (crown width RGR, 130.4 ± 30.4 %/year) without statistical significant difference (ANOVA, *p*=0.12, Figure 4.28 b).

P. cerasoides also achieved highest root collar diameter RGR (121.1 ± 28.1 %/year), followed by *M. azedarach* and *P. emblica* (119.0 ± 14.2 %/year and 109.2 ± 20.6 %/year, respectively). In contrast, root collar diameter RGR of *S. pinnata, H. glabra* and *C. axillaris* seedlings was low (21.7 ± 11.7 %/year, 22.2 ± 12.3 %/year and 24.2 ± 61.8 %/year, respectively, Figure 4.28 c).

The average seedling health score (from 0=dead to 3=perfect health) across all species was 1.9 ± 0.1. Seedlings of both two sowing treatments had average health scores of above 1.5. *P. emblica* and *A. microsperma* seedlings were the healthiest (scoring 2.8 on average), whilst, seedlings of *A. fraxinifolius, D. glandulosa, G. arborea,* and *H. dulcis* were unhealthy scoring less than 1.0 on average (0.5, 0.9, 0.5 and 0.7, respectively, Figure 4.29).
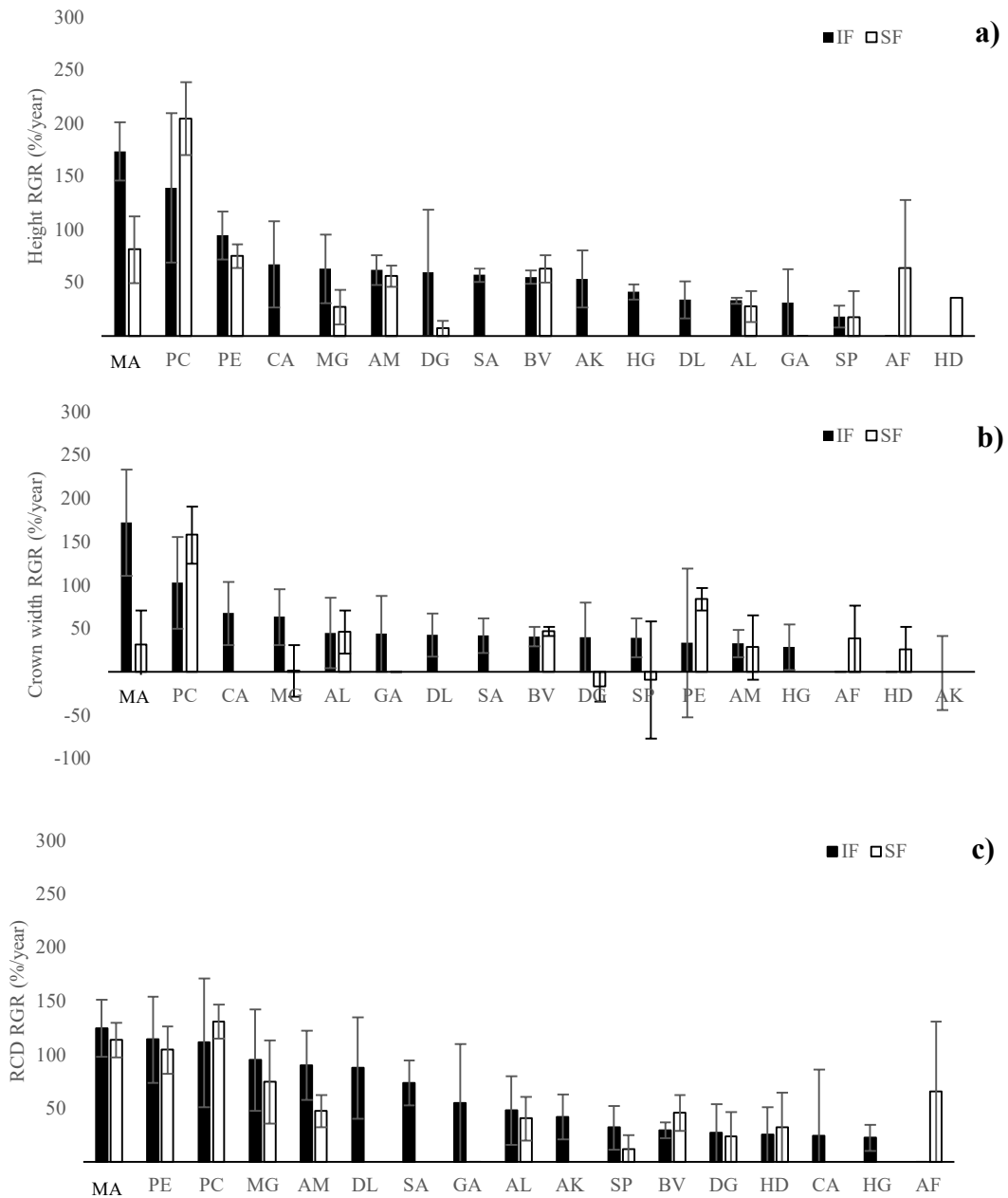
Figure 4.27 Comparison of mean (± SE) height, crown width and root collar diameter relative growth rate (RGR) of 1 year direct-seeded seedlings in the field by species between two sowing periods, IF = sown at collection time, SF=Stored and sown at the beginning of rainy season (N=3). a) Height RGR, b) Crown width RGR and c) Root collar diameter (RCD) RGR. Species; AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MG=*M. garrettii*, MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*
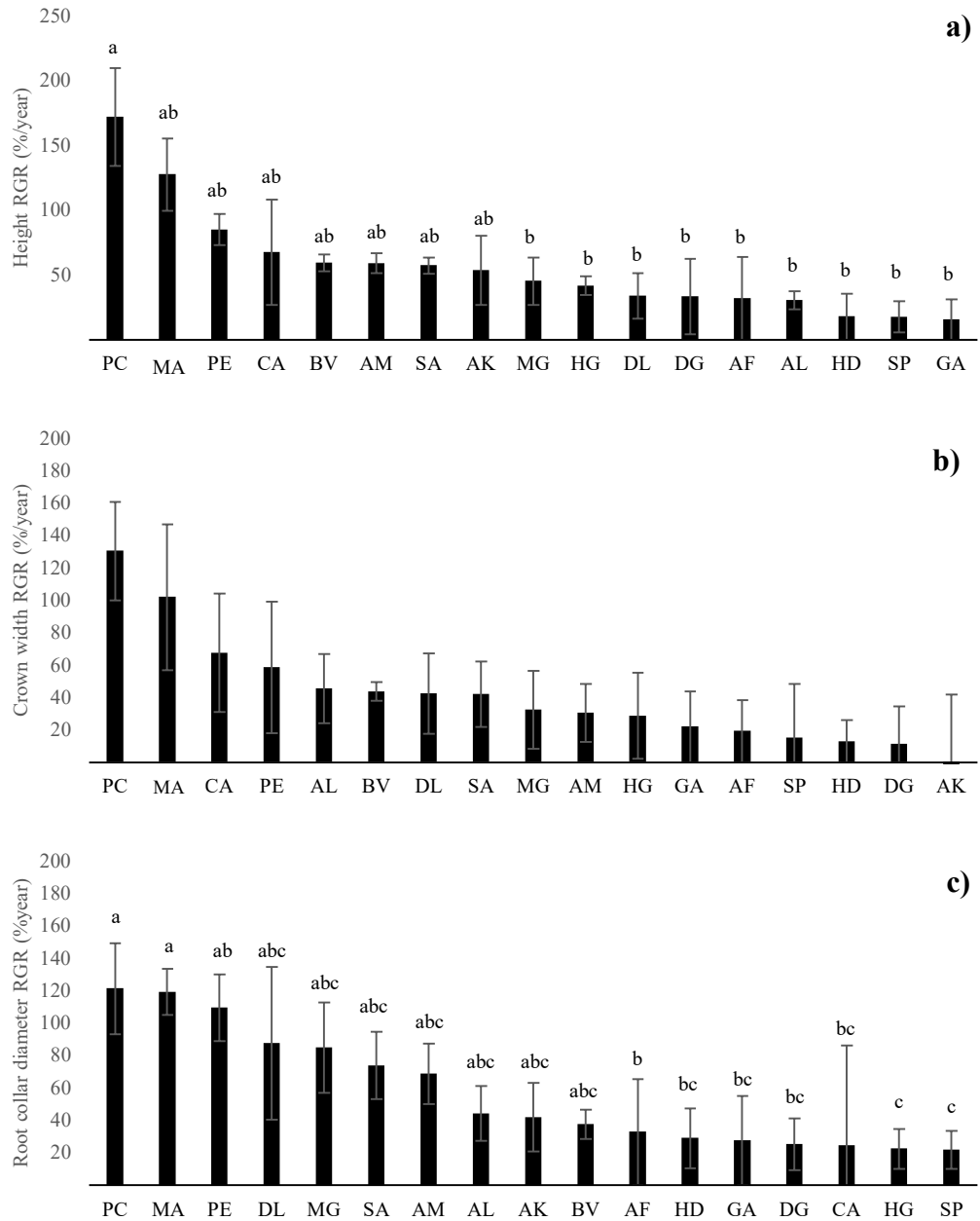
Figure 4.28 Comparison of mean (± SE) relative growth rate (RGR) of one year direct-seeded seedlings in the field. a) Height RGR, b) Crown width RGR and c) Root collar diameter RGR, calculated from two seed sowing times, at collection time and beginning of rainy season after storage (N=6). Species; AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MG=*M. garrettii*, MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.* Columns not sharing the same superscript letter are significantly different (Turkey's HSD, α= 0.05).
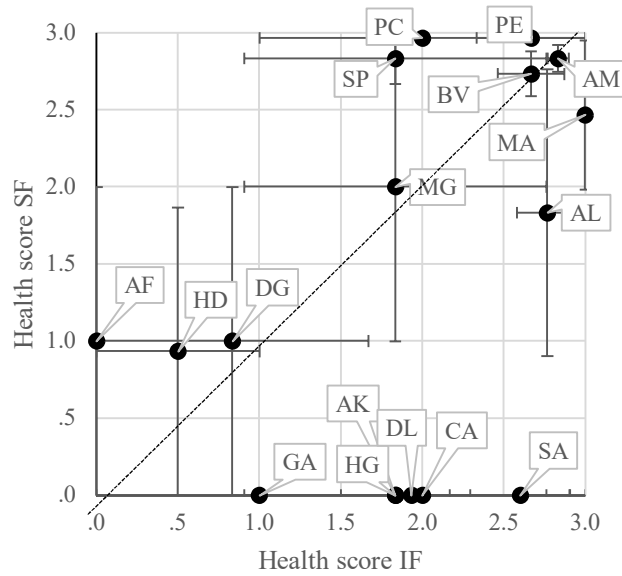
Figure 4.29 Comparison of mean (±SE) health score of one year direct-seeded seedlings in the field between two sowing periods, IF = sown at collection time, SF= Stored and sown at the beginning of rainy season (N=3). Dashed line indicates axis X equals axis Y. AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii*, PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

4.3.5 Relationship between Seed Size and Other Factors

Correlations between dry seed mass or seed size of studied species and tested factors (germination, MLD, percent yield, height RGR, crown width RGR and RCD RGR) were very low or non-existent (r^2 =0.0015, 0.017, 0.0056, 0.1119, 0.0605 and 0.1356 respectively, Figures 4.30 and 4.31).
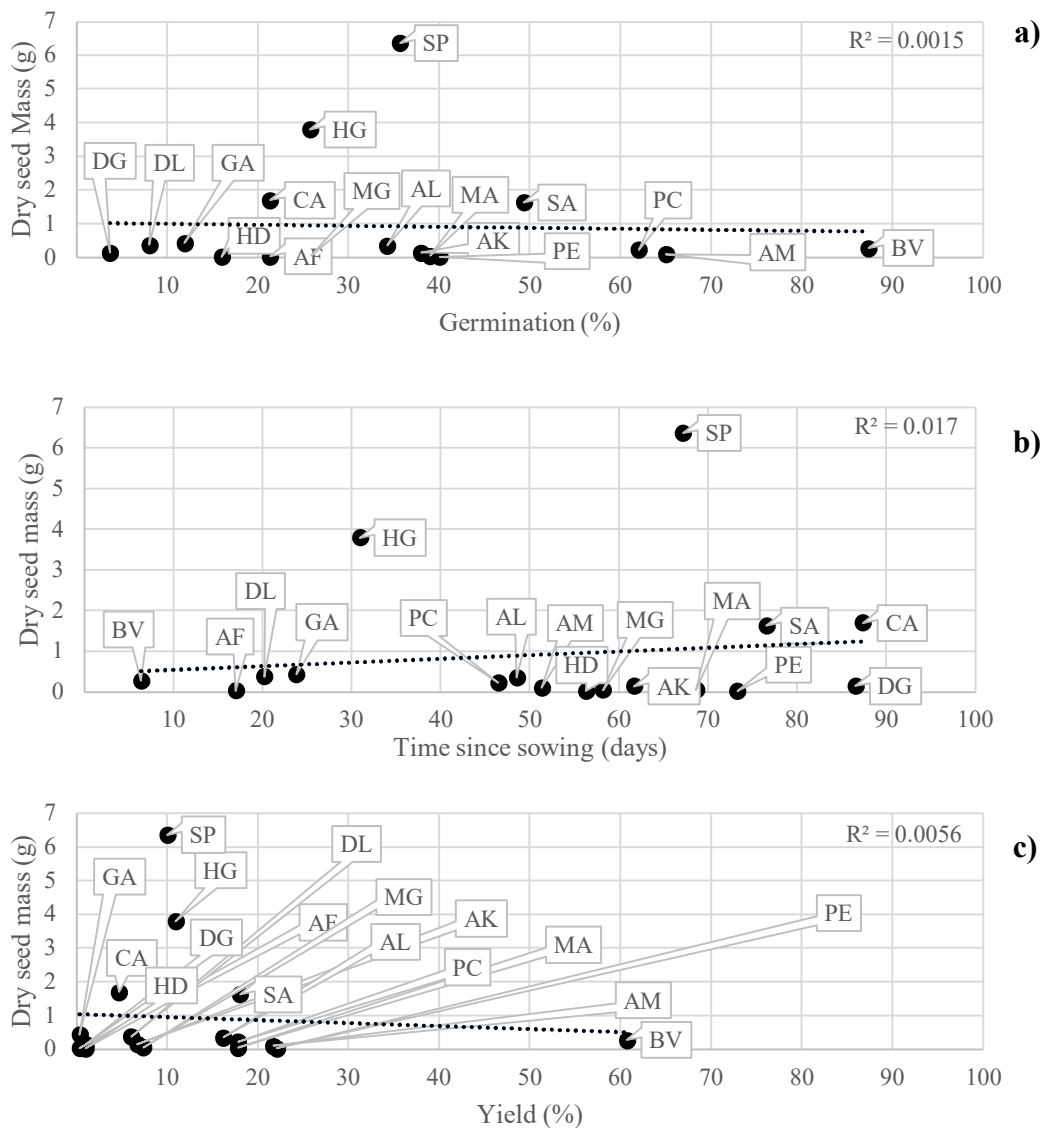
Figure 4.30 Relationship between dry seed mass (g) and a) percent germination, b) median length of dormancy (days) and c) percent yield; AF=*A. fraxinifolius,* AM=*A. microsperma,* AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii*, PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*
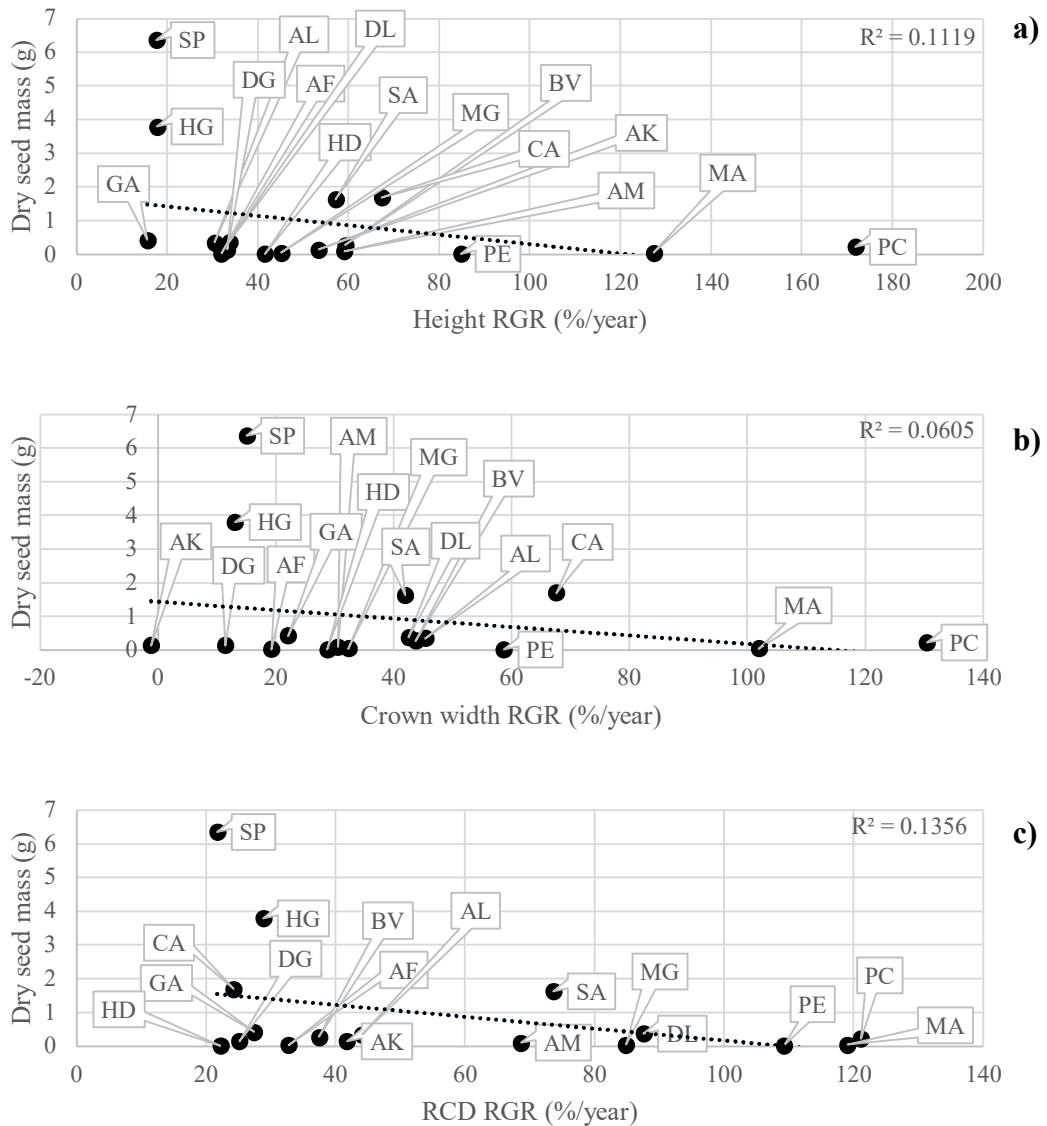
Figure 4.31 Relationship between dry seed mass (g) and a) height RGR (%/year), b) crown width (%/year) and c) RCD RGR (%/year),; AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii*, PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

4.3.6 Relative Species Performance Indices (RSPI's)

Firstly, correlation analysis was performed to determine inter-relationships among the size and RGR measurements for height, CW and RCD, to identify the most appropriate variable to use for the SI calculation. Absolute height, crown width and root collar diameter (1 year after sowing) were all strongly and significantly correlated: i) height and crown width (r=0.96, $p<0.01$, N=17, Figure 4.32 a), ii) height and root collar diameter (r=0.80, $p<0.01$, N=17, Figure 4.32 b) and iii) crown width and root collar diameter (r=0.80, $p<0.01$, N=17, Figure 4.32 c). RGR values were also correlated, but slightly less strongly than the absolute size variables: i) height and crown width RGR (r=0.90, $p<0.01$, N=17, Figure 4.33 a), ii) height and root collar diameter (r=0.76, $p<0.01$, N=17, Figure 4.33 b) and iii) crown width and root collar diameter (r=0.73, $p=0.01$, N=17, Figure 4.33 c). Therefore, the SI results could be performed using any of these growth indicators.

In this study, 1-year seedling height was selected as the main factor since it was strongly correlated with the other parameters and also measuring height could be done with less error in the field, compared with the other parameters. A *relative* species performance index RSPI was calculated from the absolute 1-year seedling height multiplied by seeding yield, expressed as a per cent of the highest score, i.e. *B. variegata* = 100, followed by *P. cerasoides*, *M. azedarach*, *P. emblica* and *A. microsperma* (SI=84, 45.3, 25.8 and 17.4, respectively, Table 4.9).

In addition, another RSPI was calculated replacing absolute height with RGR height. Using this substitution did not change the order of the top five species compared with the RSPI using absolute height. *B. variegata* showed the highest (100) followed by *P. cerasoides*, *M. azedarach*, *P. emblica* and *A. microsperma* (RSPI = 85.2, 63.1, 52.1 and 35.6, respectively, Table 4.10).

A third calculation method was based on i) seedling volume increment (calculated by combining relative growth rate data using height, crown width and RCD) and ii) percent yield. The proportion of these two factors were equally weight. This calculation method produced a slightly different result. The top five species remained the same but in a different order. *P. cerasoides* exhibited the highest species performance (SI=64.7), followed by *B. variegata, M. azedarach, P. emblica* and *A. microsperma* (SI=51.6, 50.5, 38.3 and 23.3, respectively). The remaining species had RSPI values of less than half that

of the best performing species, with *G. arborea* having the lowest (SI= 0.5, Table 4.11).
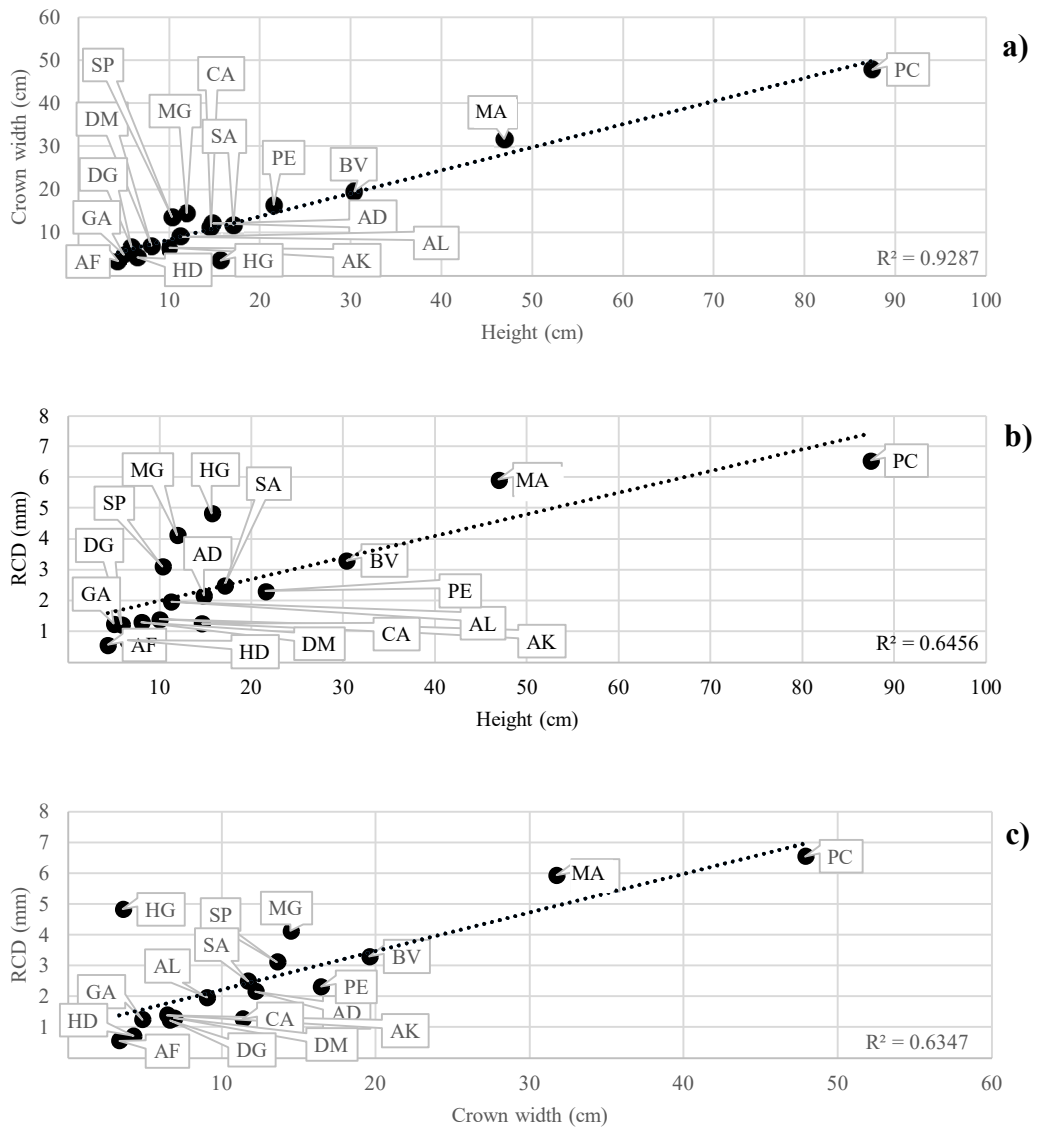
Figure 4.32 Relation of mean height, crown width and root collar diameter of one year direct-seeded seedlings in the field. Plotted from 17 species, three replicates in two sowing treatments (N=17). a) Height and crown width, b) Height and root collar diameter and c) Crown width and root collar diameter. Dotted line indicates trend of relation. Species; AF=*A. fraxinifolius*, AM=*A. microsperma*, AK=*A. kurzii*, AL=*A. lacucha*, BV=*B. variegata*, CA=*C. axillaris*, DL=*D. longan*, DG=*D. glandulosa*, GA=*G. arborea*, HG=*H. glabra*, HD=*H. dulcis*, MG=*M. garrettii*, MA= *M. azedarach*, PE=*P. emblica*, PC=*P. cerasoides*, SP=*S. pinnata*, SA=*S. albiflorum*.
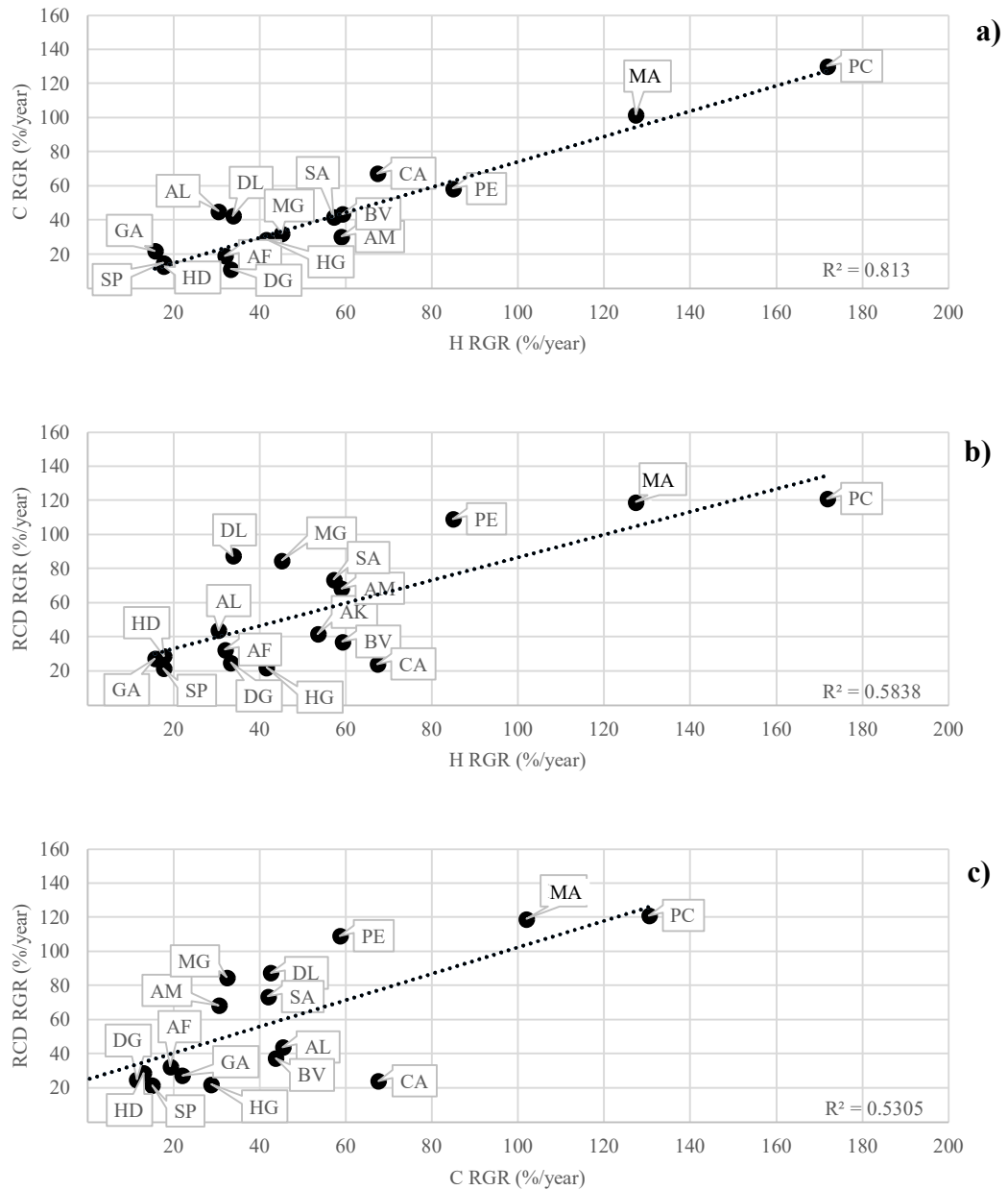
Figure 4.33 Relation of mean height, crown width and root collar diameter relative growth rate (H RGR, C RGR and R RGR, respectively) of one year direct-seeded seedlings in the field. Plotted from 17 species, three replicates in two sowing treatments (N=17). a) H RGR and C RGR, b) H RGR and R RGR and c) R RGR and C RGR. Dotted line indicates trend of relation. Species; AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MG=*M. garrettii*, MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

84

Table 4.9 Relative Species Performance Index (RSPI), calculation of growth index of height of direct-seeded seedlings over one year in the field.

Species	% Yield (Y)	Mean Height (cm) (H)	Y x H	RSPI
Bauhinia variegata	60.7	30.4	1841.2	100.0
Prunus cerasoides	17.8	87.4	1555.7	84.5
Melia azedarach	17.8	46.9	834.5	45.3
Phyllanthus emblica	22.1	21.5	474.8	25.8
Adenanthera microsperma	21.7	14.8	320.3	17.4
Syzygium albiflorum	18.0	17.1	307.2	16.7
Artocarpus lacucha	16.2	11.2	181.6	9.9
Horsfieldia glabra	10.9	15.7	170.8	9.3
Spondias pinnata	10.0	10.3	102.8	5.6
Manglietia garrettii	7.3	11.9	87.1	4.7
Choerospondias axillaris	4.7	14.6	68.0	3.7
Alangium kurzii	6.7	10.0	66.4	3.6
Dimocarpus longan	6.0	8.0	48.0	2.6
Hovenia dulcis	1.0	6.5	6.5	0.4
Diospyros glandulosa	1.0	5.8	5.8	0.3
Acrocarpus fraxinifolius	0.3	4.3	1.4	0.1
Gmelina arborea	0.3	5.0	1.7	0.1

Table 4.10 Relative Species Performance Index (RSPI), calculation of growth index of height relative growth rate of direct-seeded seedlings over one year in the field.

Species	% Yield (% E)	Mean H RGR (H)	% E x H	RSPI
Bauhinia variegata	60.7	59.2	3,588.4	100.0
Prunus cerasoides	17.8	171.8	3,057.2	85.2
Melia azedarach	17.8	127.3	2,265.9	63.1
Phyllanthus emblica	22.1	84.8	1,871.3	52.1
Adenanthera microsperma	21.7	59.0	1,277.3	35.6
Syzygium albiflorum	18.0	57.1	1,028.4	28.7
Artocarpus lacucha	16.2	30.4	491.5	13.7
Alangium kurzii	6.7	53.4	356.2	9.9
Manglietia garrettii	7.3	45.1	330.6	9.2
Choerospondias axillaris	4.7	67.3	314.1	8.8
Dimocarpus longan	6.0	33.7	202.2	5.6
Horsfieldia glabra	10.9	17.7	192.6	5.4
Spondias pinnata	10.0	17.6	176.0	4.9
Hovenia dulcis	1.0	41.5	41.5	1.2
Diospyros glandulosa	1.0	33.2	33.2	0.9
Acrocarpus fraxinifolius	0.3	31.9	10.6	0.3
Gmelina arborea	0.3	15.6	5.2	0.1

Table 4.11 Relative Species Performance Index (RSPI), calculation of growth index of relative growth rate (RGR) of direct-seeded seedlings over one year in the field.

Species	% Yield	Relative Yield	Growth Index (GI)*	Relative Growth Index	RSPI**
Prunus cerasoides	17.8	29.3	659,021.8	100.0	64.7
Bauhinia variegata	60.7	100.0	21,693.1	3.3	51.6
Melia azedarach	17.8	29.3	472,071.4	71.6	50.5
Phyllanthus emblica	22.1	36.4	264,658.4	40.2	38.3
Adenanthera microsperma	21.7	35.7	72,515.3	11.0	23.3
Syzygium albiflorum	18.0	29.7	81,098.2	12.3	21.0
Artocarpus lacucha	16.2	26.6	15,480.6	2.3	14.5
Manglietia garrettii	7.3	12.1	84,830.3	12.9	12.5
Dimocarpus longan	6.0	9.9	67,556.6	10.3	10.1
Horsfieldia glabra	10.9	18.0	5,396.6	0.8	9.4
Spondias pinnata	10.0	16.5	2,183.6	0.3	8.4
Alangium kurzii	6.7	11.0	24,350.4	3.7	7.3
Choerospondias axillaris	4.7	7.7	10,380.7	1.6	4.6
Diospyros glandulosa	1.0	1.6	5,490.0	0.8	1.2
Hovenia dulcis	1.0	1.6	3,847.3	0.6	1.1
Acrocarpus fraxinifolius	0.3	0.5	8,926.5	1.4	1.0
Gmelina arborea	0.3	0.5	3,097.3	0.5	0.5

*Growth Index was calculated from Seedling volume ($1/3 \pi$ x r^2 x H) + RCR Crown width, r= RGR Root collar diameter divided by 2, H= RGR height.
** Species Performance Index calculated from (Relative Yield + Relative Growth Index)/2

4.3.7 Seedling Sturdiness

Seedling sturdiness was calculated from seedling height (cm) divided by root collar diameter (mm). Good quality planting stock, raised in a nursery, is considered sturdy if this index is <10. The mean sturdiness quotient, across all species, was 5.3 ± 0.5, ranging from 0.7 in *G. arborea* to 12.9 in *C. axillaris* (Figure 4.34). The sturdiness quotient was mostly did not differ significantly between the two sowing periods. While, *M. azedarach* seedlings from seeds sown at collection time were more sturdy than those sown after storage (sturdiness quotient lower by 3.5, *t*-test, *p*=0.04, Figure 4.35).
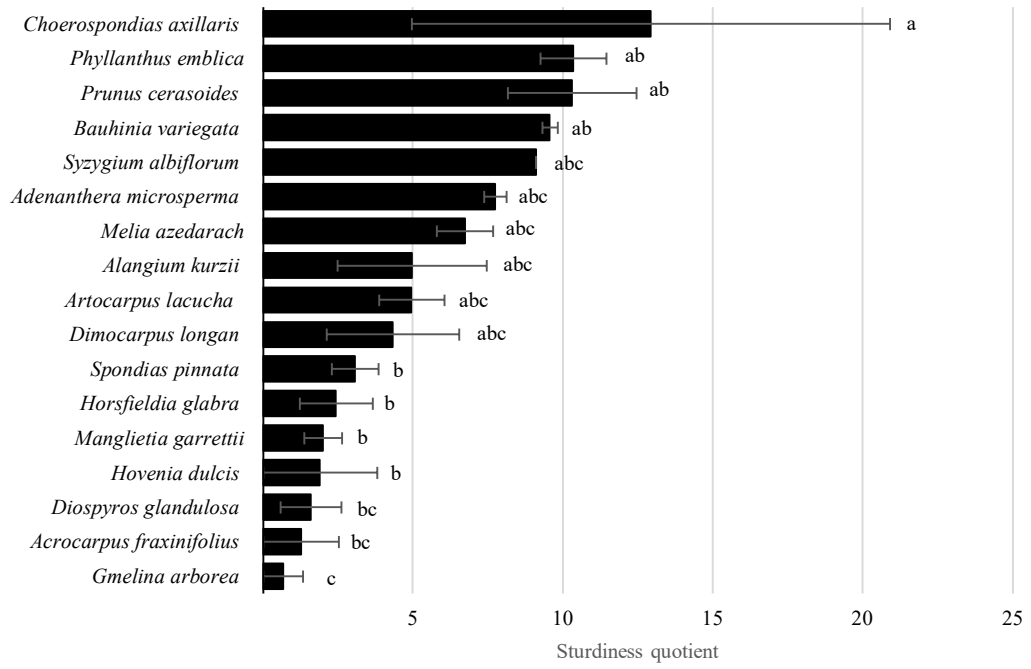
Figure 4.34 Sturdiness quotient of one year direct-seeded seedlings in the field, calculated from two seed sowing times, at collection time and beginning of rainy season after storage. Columns not sharing the same superscript letter are significantly different (Turkey's HSD, α= 0.05).
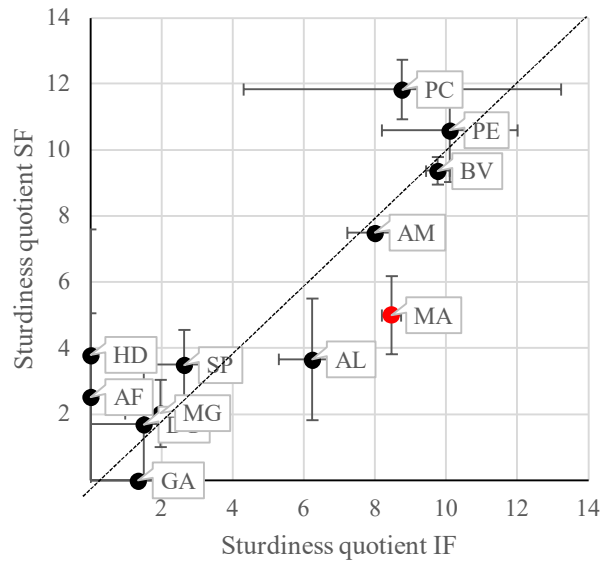
Figure 4.35 Comparison of mean (± SE) sturdiness quotient of one year direct-seeded seedlings in the field between two sowing periods, IF = sowing immediately at collecting time, SF=Stored and sown in the field (N=3). Red circles indicate significant difference between the two bars within each species (t-test, $p < 0.05$). Dashed line indicates axis X equals axis Y. AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

4.3.8 Nursery-raised seedlings

Seedling survival

The mean (± SE) percent seedlings survival, across species, was 40.9 ± 3.5 %. *H. glabra* and *A. kurzii* presented the lowest percent seedling survival (3.3 ± 1.7 % and 10.1 ± 1.8 % respectively). In contrast, *M. azedarach, A. microsperma* and *D. longan* survived well in the field with high percentages (72.7 ± 10.5 %, 78.6 ± 6.6 % and 79.7 ± 4.6 %, respectively, Figure 4.36).
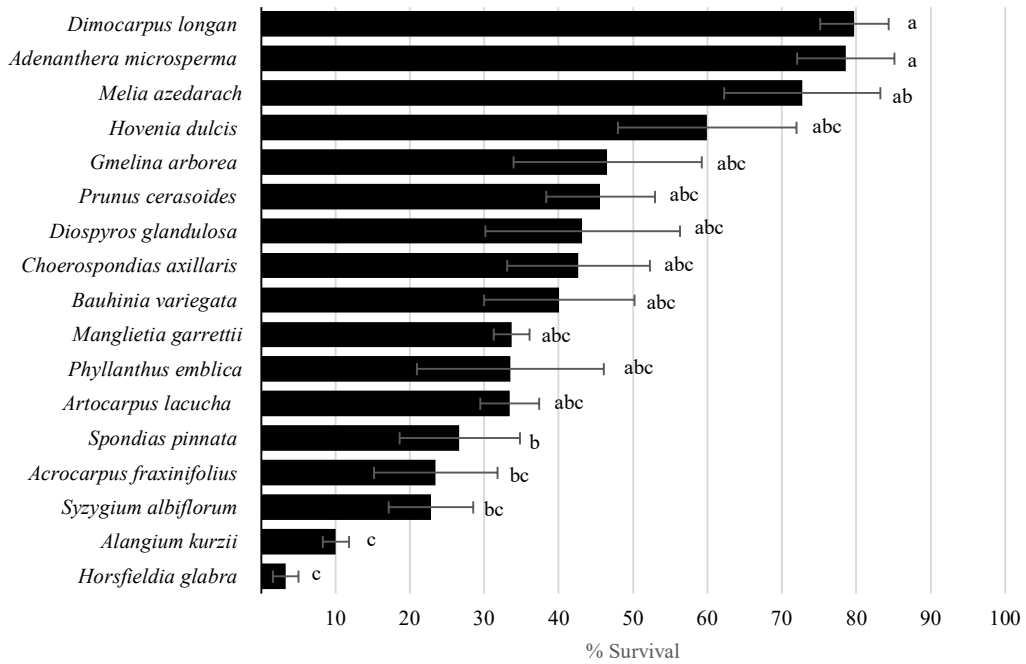
Figure 4.36 Comparison of percent survival of nursery raised-seedlings over one year in the field. Columns not sharing the same superscript letter are significantly different (Turkey's HSD, α= 0.05).

Seedling Growth

Seedling height, averaged across all species, one year after planting was 82.7 ± 9.9 cm. *M. azedarach* seedlings were the tallest (268.0 ± 60.8 cm), whilst *D. longan* seedlings were the shortest (21.3 ± 1.4 cm, Figure 4.37 a). Mean crown width, averaged across species, was 57.0 ± 5.5 cm. *M. azedarach* also showed the greatest crown expansion (142.5 ± 28.2 cm), whilst *H. glabra* achieved the least (18.3 ± 9.9 cm, Figure 4.37 b). Mean RCD averaged across species was 12.5 ± 1.2 mm. *G. arborea* presented the largest root collar diameter (28.3± 4.8 mm), whilst *H. glabra* presented the smallest (4.5 ± 2.3 mm, Figure 4.37 c).
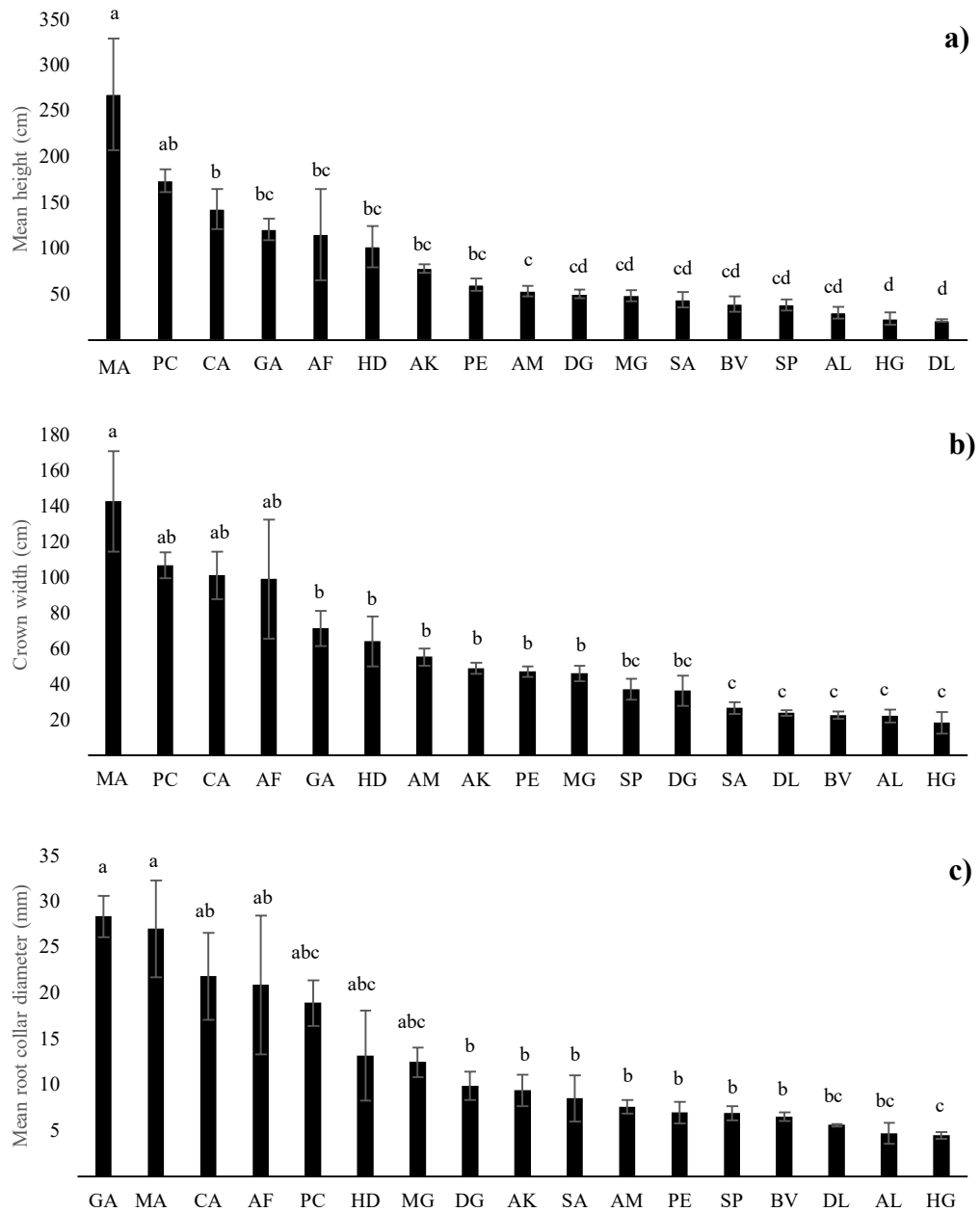
Figure 4.37 Comparison of seedlings performance of 1-year nursery-raised seedlings in the field, N=3. a) Mean seedling height b) Mean seedling crown width c) Mean root collar diameter. Species; AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MG=*M. garrettii*, MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.* Columns not sharing the same superscript letter are significantly different (Turkey's HSD, α= 0.05).

Relative growth rates (RGR) of nursery-raised seedlings were calculated 1 year after planting. The mean height RGR, averaged across species, was 126.7 ± 16.8 %. *M. azedarach* achieved the highest growth rate (290.6 ± 50.5 %/year) and other five species exceeded 200 %/year; *G. arborea* (286.4 ± 37.9 %/year), *C. axillaris* (248.6 ± 11.4 %/year), *P. cerasoides* (227.8 ± 75.0 %/year), *M. garrettii* (223.0 ± 23.6 %/year) and *A. fraxinifolius* (211.7 ± 22.6 %/year). Conversely, two species showed negative height RGR, indicating damage or die back of the above-ground seedling parts: *B. variegata* (-2.0 ± 34.1 %/year) and *H. glabra* (-38.4 ± 38.1 %/year, Figure 4.38 a). The mean crown width RGR across species was 181.1 ± 25.4 %/year. *H. dulcis* presented the highest (438.4 ± 113.5 %/year) followed by *M. azedarach* (385.8 ± 9.2 %/year) and *G. arborea* (347.8 ± 46.0 %/year). Three species presented negative values; *S. pinnata* (-2.2 ± 33.4 %/year), *B. variegata* (-11.5 ± 118.4 %/year) and *H. glabra* (-68.7 ± 91.0 %/year, Figure 4.38 b). The mean root collar diameter RGR, averaged across species, was 157.9 ± 17.1 %/year. *G. arborea* achieved the highest RCR RGR (368.3 ± 59.8 %) with *P. cerasoides, C. axillaris,* and *M. azedarach* all exceeding 300 %/year (323.1 ± 11.1, 315.7 ± 17.7 and 307.1 ± 22.5 %/year, respectively). *A. lacucha* had the slowest RGR RCD (25.9 ± 30.9 %/year, Figure 4.38 c).

Seedlings generally maintained good health throughout their first year. The mean seedling health score was 2.9 ± 0.1. Most species had health scores higher than 2.5, whilst *H. glabra* was the lowest (2.0 ± 1.0, Figure 4.39).
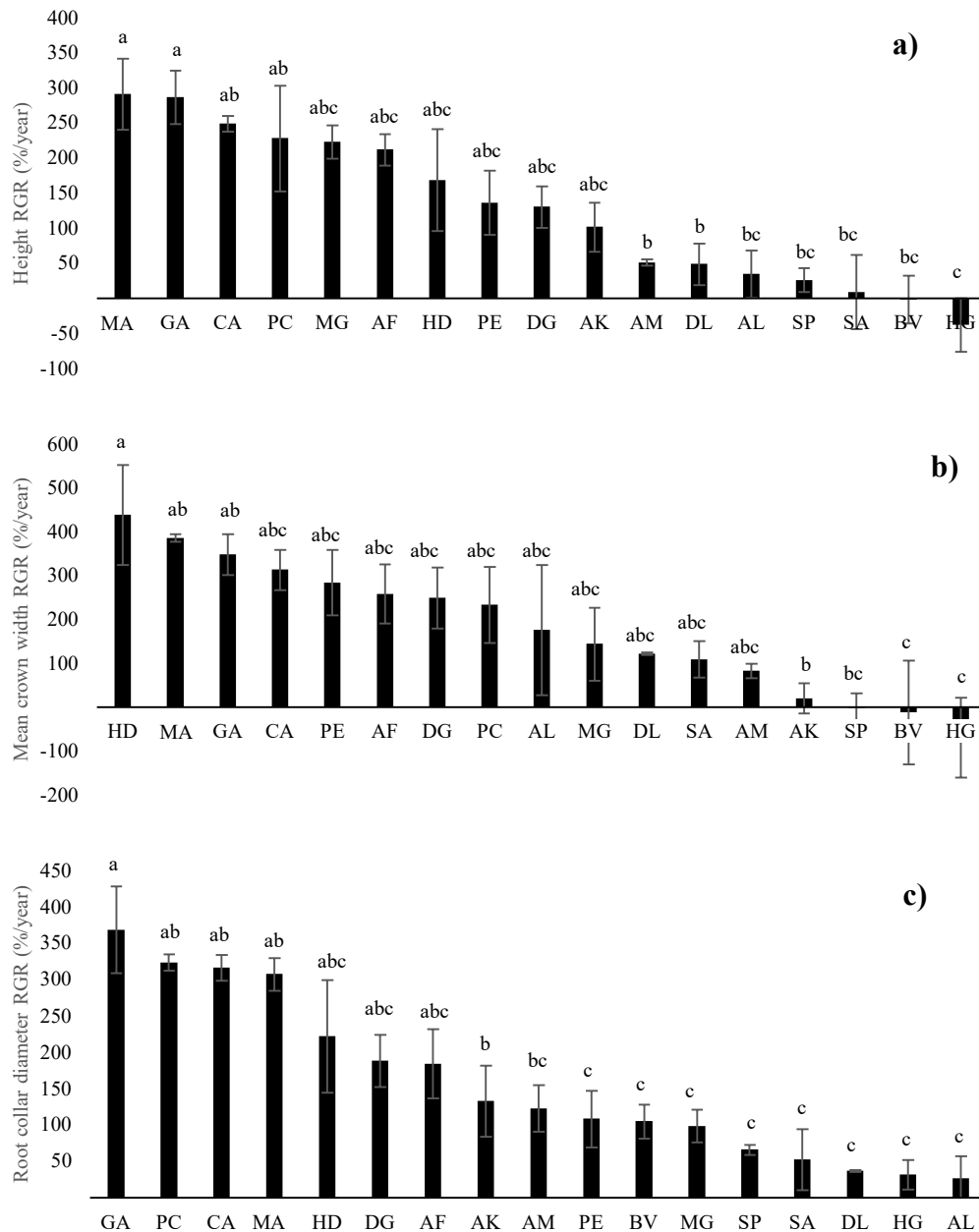
Figure 4.38 Comparison of relative growth rate (RGR) of nursery raised-seedlings in the field. a) Mean seedling height RGR b) Mean seedling crown width RGR and c) Mean root collar diameter RGR. Species; AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MG=*M. garrettii*, MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.* Columns not sharing the same superscript letter are significantly different (Turkey's HSD, α= 0.05).
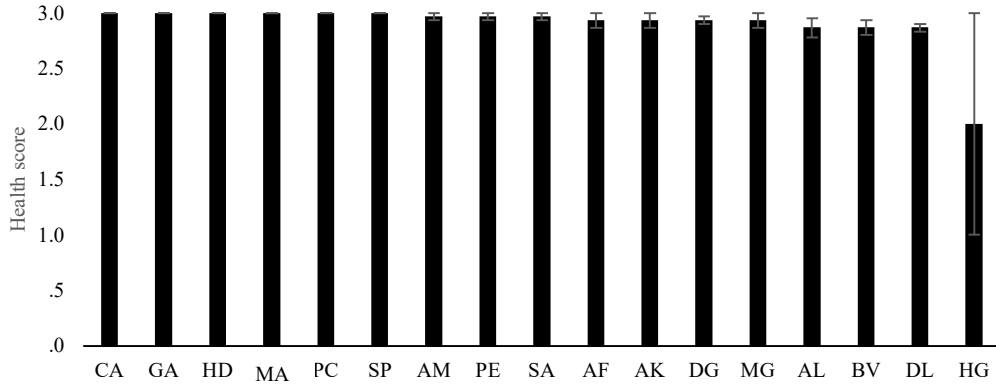
Figure 4.39 Health score of nursery raised-seedlings over one year in the field. Species; AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa,* GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MG=*M. garrettii*, MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

Seedling Sturdiness

Mean seedling sturdiness quotient, averaged across species was 6.9 ± 0.4, which is well within the limit of <10, recommended for nursery-raised planting stock. *A. kurzii* was the least sturdy species (10.4 ± 2.1) followed by *H. dulcis* (10.0 ± 2.3). *H. glabra* was the sturdiest (3.5 ± 1.8, Figure 4.40).

94
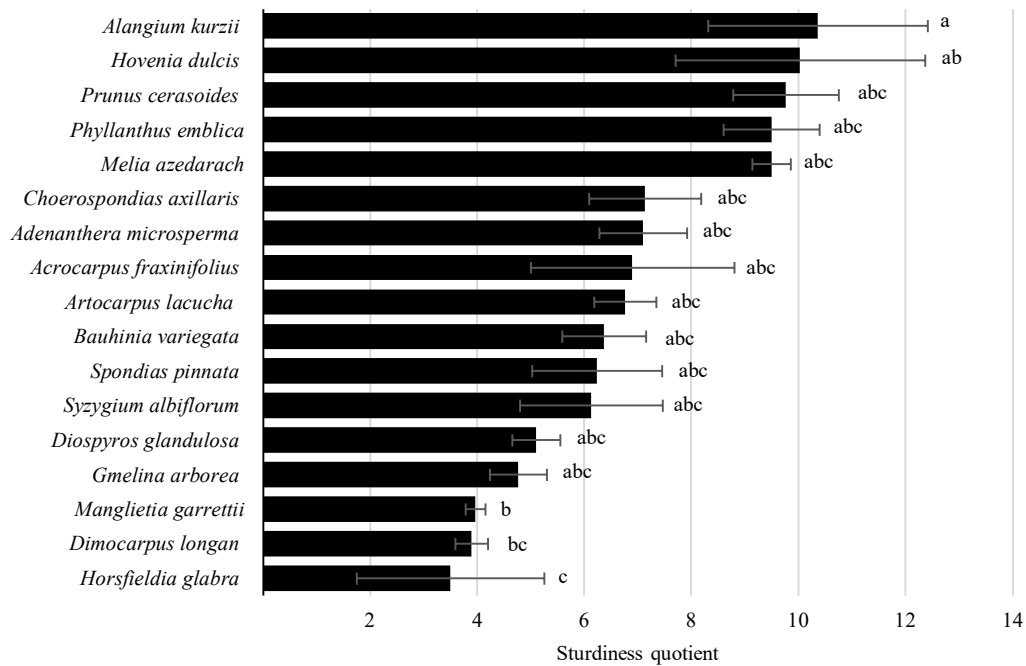
Figure 4.40 Sturdiness quotient of one year nursery raised-seedlings in the field. Columns not sharing the same superscript letter are significantly different (Turkey's HSD, α= 0.05).

Relative Species Performance Indices (RSPI's)

Size variables (height, crown width and root collar diameter) were strongly correlated with each other: i) height and crown width (r=0.96, p<0.01, N=17, Figure 4.41 a), ii) height and root collar diameter (r=0.86, p<0.01, N=17, Figure 4.41 b) and iii) crown width and root collar diameter (r=0.87, p<0.01, N=17, Figure 4.41 c), as were relative growth rates (RGR): i) height and crown width RGR (r=0.80, p<0.01, N=17, Figure 4.42 a), ii) height and root collar diameter RGR (r=0.86, p<0.01, N=17, Figure 4.42 b) and iii) crown width and root collar diameter RGR (r=0.72, p<0.01, N=17, Figure 4.42 c).

Relative Species Performance Index (RSPI) was calculated by two method, based on height RGR and growth index (combining all growth parameters) as previously described. Both indices produced similar results. Using the RGR height-based index, *M. azedarach* performed the best (SI= 100) followed by *G. arborea* (SI=63.1) and *C. axillaris* (SI=50.1) respectively. While *A. microsperma* had lowest performance (SI=49.1, Table 4.12). Similarly with the growth-based index, once again *M. azedarach* performed the best (SI= 80.9) followed by *G. arborea* (SI=79.2) and *C. axillaris* (SI=58.6) respectively. While *A. microsperma* had lowest performance (SI=7.3, Table 4.13).
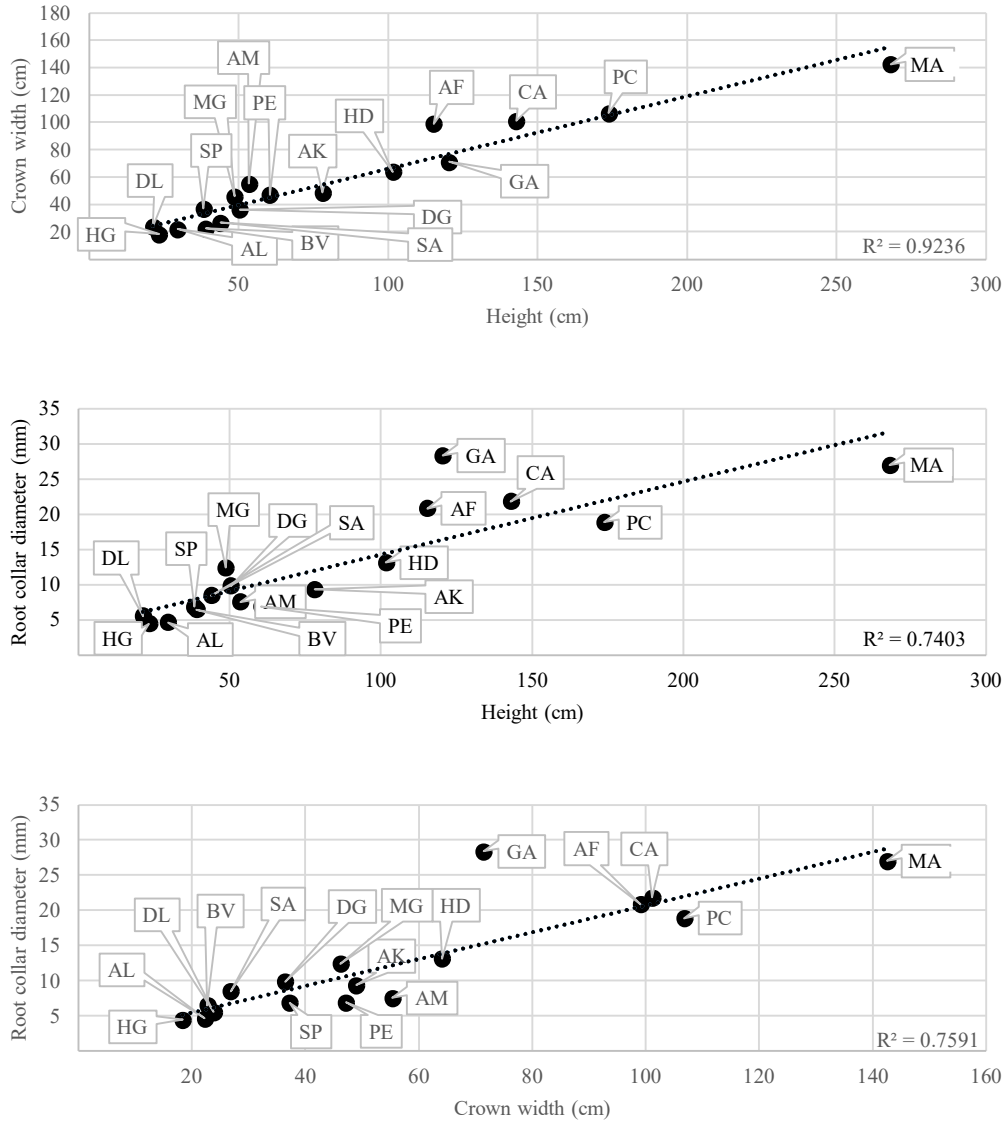
Figure 4.41 Relation of mean height, crown width and root collar diameter of one year nursery raised-seedlings in the field. Plotted from 17 species, three replicates in two sowing treatments (N=17). a) Height and crown width, b) Height and root collar diameter and c) Crown width and root collar diameter. Dotted line indicates trend of relation. Species; AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MG=*M. garrettii*, MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*
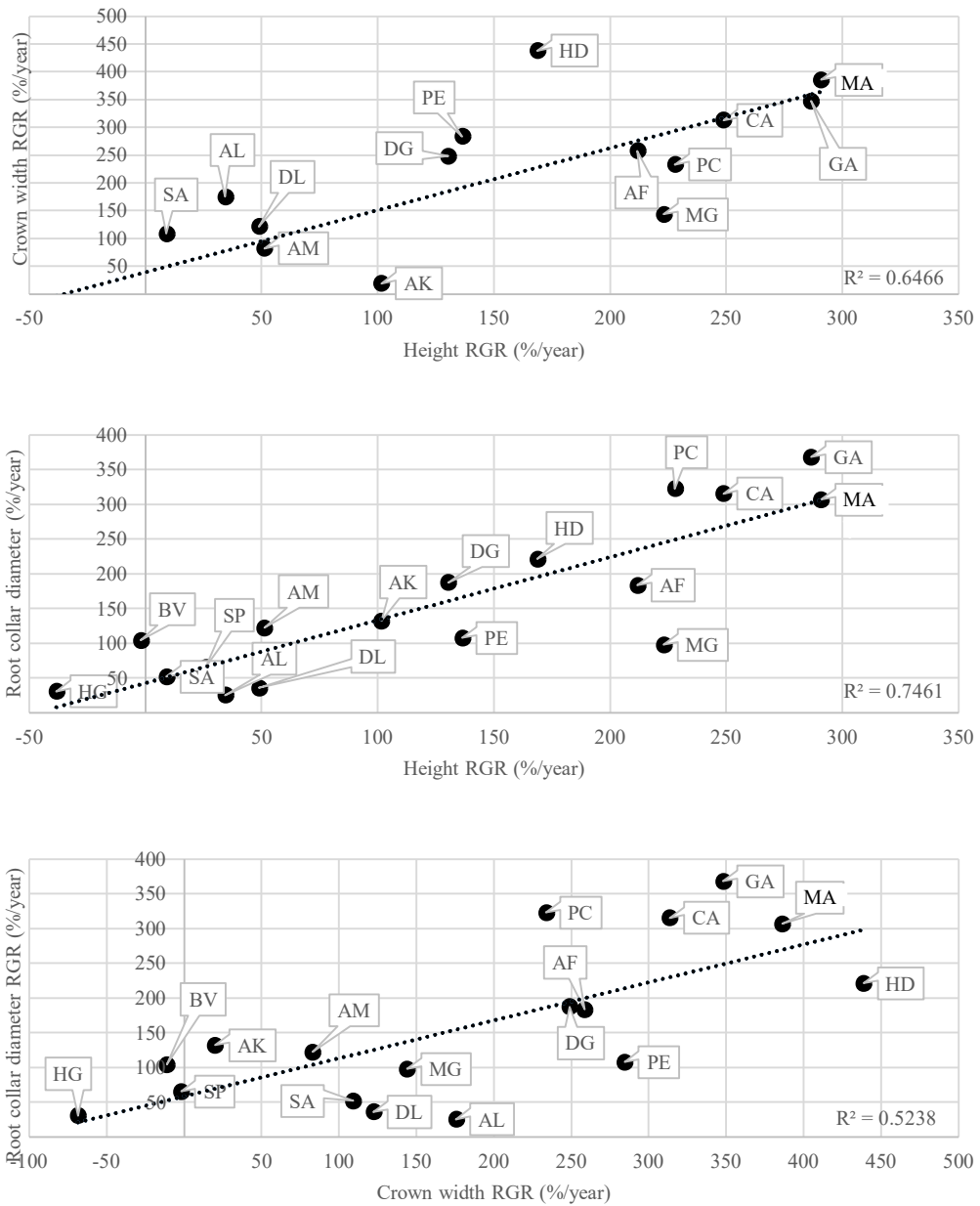
Figure 4.42 Relation of mean height, crown width and root collar diameter relative growth rate (H RGR, C RGR and R RGR, respectively) of one year nursery raised-seedlings in the field. Plotted from 17 species, three replicates in two sowing treatments (N=17). a) H RGR and C RGR, b) H RGR and R RGR and c) R RGR and C RGR. Dotted line indicates trend of relation. Species; AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MG=*M. garrettii,* MA= *M. azedarach,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

Table 4.12 Relative Species Performance Index (RSPI) based on calculation of height RGR of nursery-raised seedlings over one year in the field.

Species	% Yield (Y)	Mean H RGR (H)	Y x H	RSPI
Melia azedarach	72.7	290.6	21,136.1	100.0
Gmelina arborea	46.6	286.4	13,330.6	63.1
Choerospondias axillaris	42.6	248.6	10,599.5	50.1
Diospyros glandulosa	79.7	130.2	10,382.5	49.1
Prunus cerasoides	33.5	227.8	7,630.2	36.1
Manglietia garrettii	33.7	223.0	7,506.7	35.5
Phyllanthus emblica	45.6	136.2	6,210.5	29.4
Acrocarpus fraxinifolius	23.4	211.7	4,960.1	23.5
Alangium kurzii	33.4	101.5	3,388.4	16.0
Artocarpus lacucha	78.6	34.3	2,692.2	12.7
Dimocarpus longan	43.2	48.8	2,106.2	10.0
Spondias pinnata	22.8	25.9	590.6	2.8
Hovenia dulcis	3.3	168.5	555.2	2.6
Adenanthera microsperma	10.1	51.1	514.7	2.4
Syzygium albiflorum	26.7	9.0	240.0	1.1
Bauhinia variegata	40.1	- 2.0	-81.5	- 0.4
Horsfieldia glabra	59.9	-38.4	-2,299.8	-10.9

Table 4.13 Relative Species Performance Index (RSPI) based on calculation of growth index of nursery-raised seedlings over one year in the field.

Species	% Seedling Yield	Relative Yield	Growth Index (GI)*	Relative Growth Index	RSPI**
Melia azedarach	72.7	91.2	7,172,603.4	70.6	80.9
Gmelina arborea	46.6	58.4	10,166,413.5	100.0	79.2
Choerospondias axillaris	42.6	53.5	6,483,651.7	63.8	58.6
Diospyros glandulosa	79.7	100.0	1,202,983.8	11.8	55.9
Prunus cerasoides	33.5	42.0	6,223,266.3	61.2	51.6
Artocarpus lacucha	78.6	98.6	6,174.6	0.1	49.3
Horsfieldia glabra	59.9	75.2	-9,883.2	-0.1	37.6
Phyllanthus emblica	45.6	57.2	416,849.5	4.1	30.6
Dimocarpus longan	43.2	54.2	16,936.6	0.2	27.2
Bauhinia variegata	40.1	50.3	-5,825.4	-0.1	25.1
Acrocarpus fraxinifolius	23.4	29.4	1,873,372.9	18.4	23.9
Manglietia garrettii	33.7	42.2	561,315.9	5.5	23.9
Alangium kurzii	33.4	41.9	464,974.1	4.6	23.2
Syzygium albiflorum	26.7	33.5	6,509.6	0.1	16.8
Spondias pinnata	22.8	28.6	29,213.8	0.3	14.5
Hovenia dulcis	3.3	4.1	2,166,667.4	21.3	12.7
Adenanthera microsperma	10.1	12.6	200,318.8	2.0	7.3

*Growth Index was calculated from seedling volume (1/3 π x r^2 x H) + RCR Crown width, r= RGR Root collar diameter divided by 2, H= RGR height.
** Species Performance Index calculated from (Relative Yield + Relative Growth Index)/2

4.3.9 Growth Comparison of Direct Seeded and Nursery-raised seedlings

Since size variables (height, CW and RCD, after 1 year) were strongly correlated (as shown in the previous sections), only one variable – height – was used in the following analysis. Direct-seeded seedlings grew less tall than nursery-raised seedlings (averaged across species), one year after planting. The mean heights of 1-year-old direct-seeded seedlings (DS) were close to the initial planting heights of nursery-raised seedlings (NS) of 7 species: *A. lacucha* (DS ages 12 Months = 11.9 cm and NS age 8 months = 13.2 cm), *B. variegata* (DS ages 12 months = 28.0 cm and NS ages 10 months = 27.1 cm), *C. axillaris* (DS ages 8 months = 24.0 cm and NS ages 8 months = 24.1 cm), *D. longan* (DS ages 12 months =13.0 cm and NS ages 9 months = 13.6 cm), *H. glabra* (DS ages 12 months = 19.5 cm and NS ages 13 months = 25.3 cm), *P. emblica* (DS ages 12 months = 25.4 cm and NS ages 14 months = 30.7 cm) and *S. albiflorum* (DS ages 12 months = 18.5 cm and NS ages 15 months = 22.1 cm)

For three species, 1-year-old direct-seeded seedlings were about twice as tall as the initial height of nursery-raised seedlings; *M. garrettii* (DS ages 12 months = 24.4 cm and NS ages 14 months = 13.5 cm), *M. azedarach* (DS ages 12 month = 61.2 cm and NS = 37.5 cm) and *P. cerasoides* (DS ages 12 months = 95.9 cm and NS ages 5 months = 35.7, Figure 4.43)

For *A. fraxinifolius*, *D. glandulosa*, *G. arborea* and *H. dulcis* results were available only from nursery-raised seedlings, since germination and seedling establishment from direct seeding was unsuccessful.
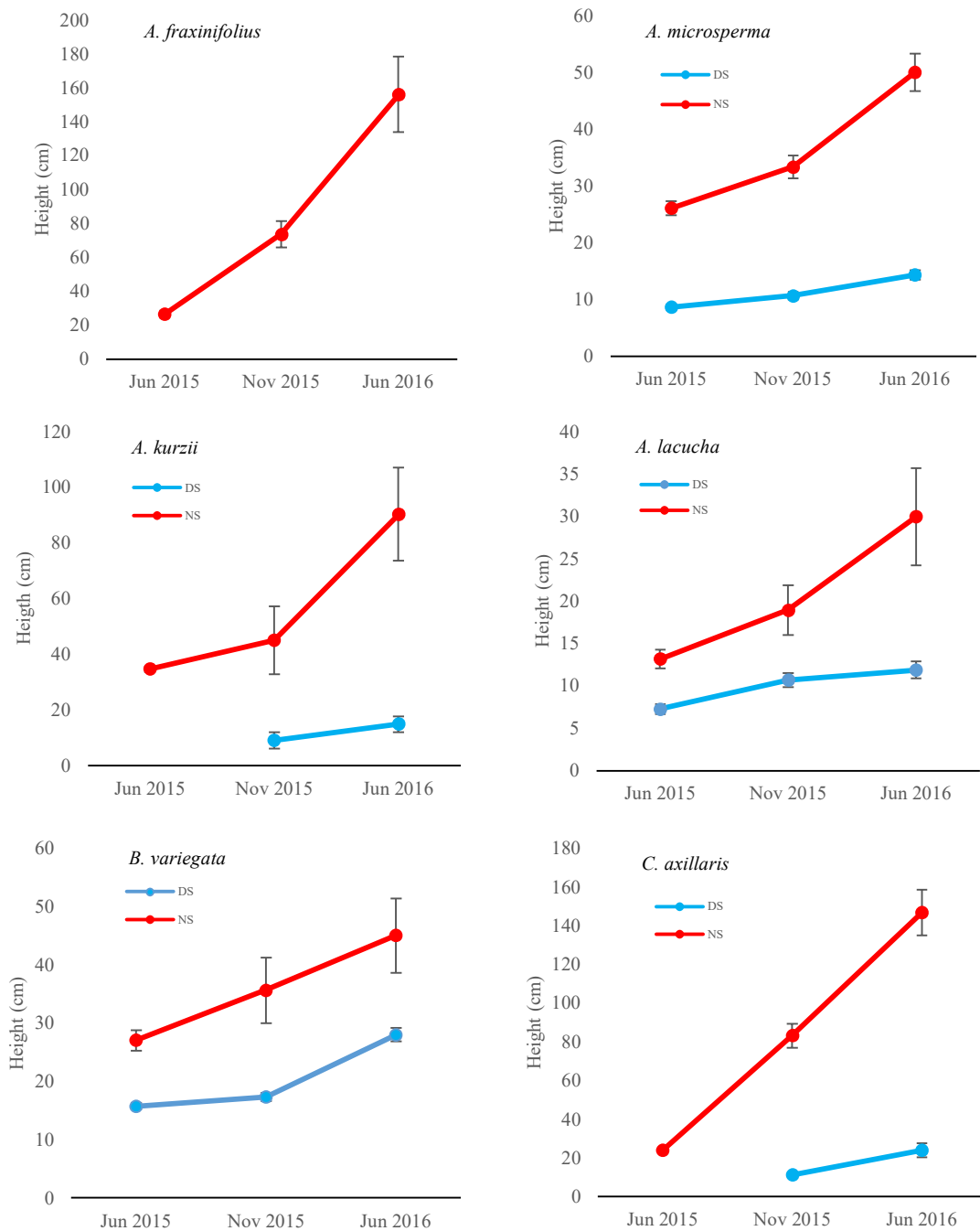
Figure 4.43 Comparison of mean height (±SE) of direct seeded and nursery-raised seedlings of 17 tree species in the field, monitored at 3 periods.
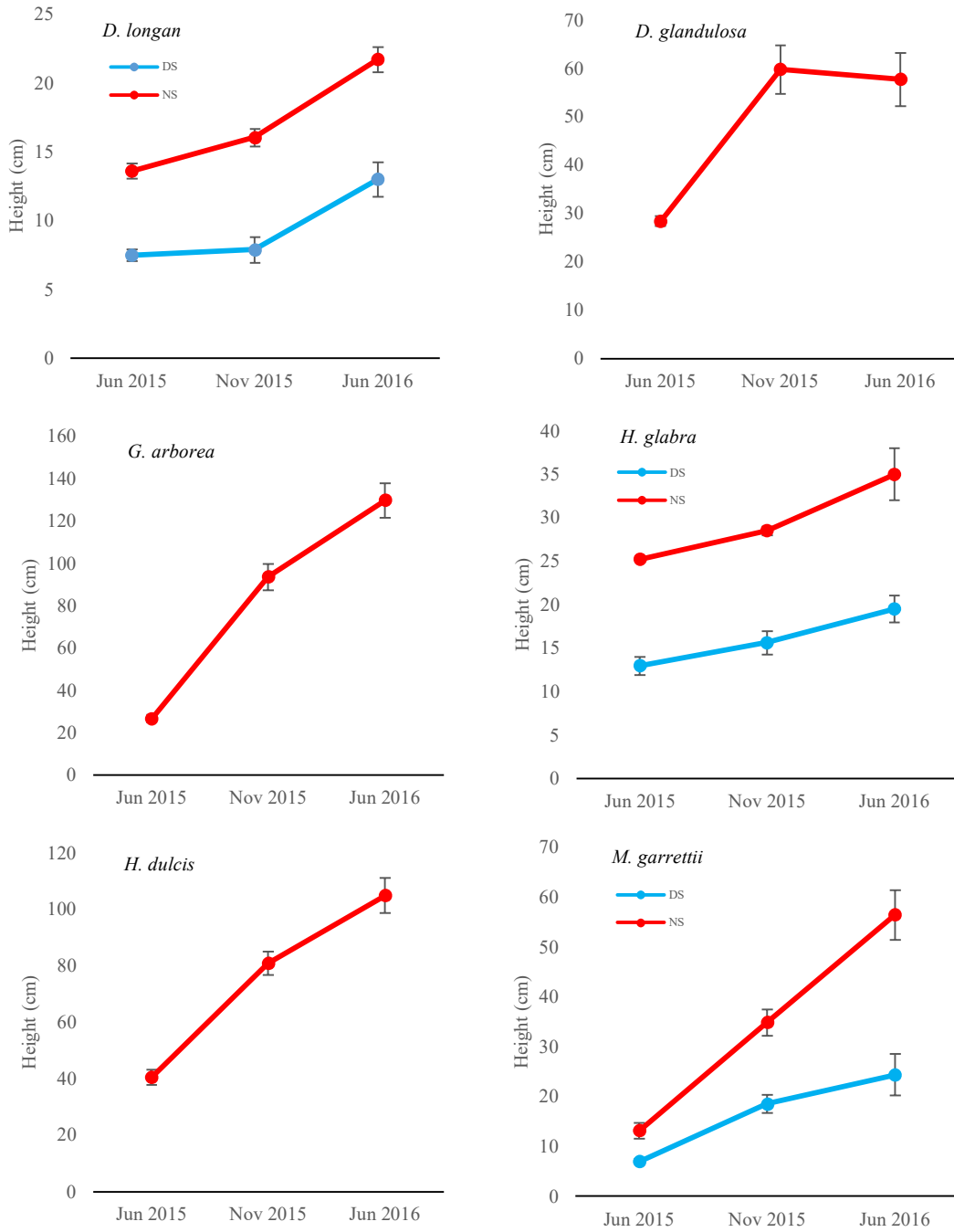
Figure 4.43 Continued.
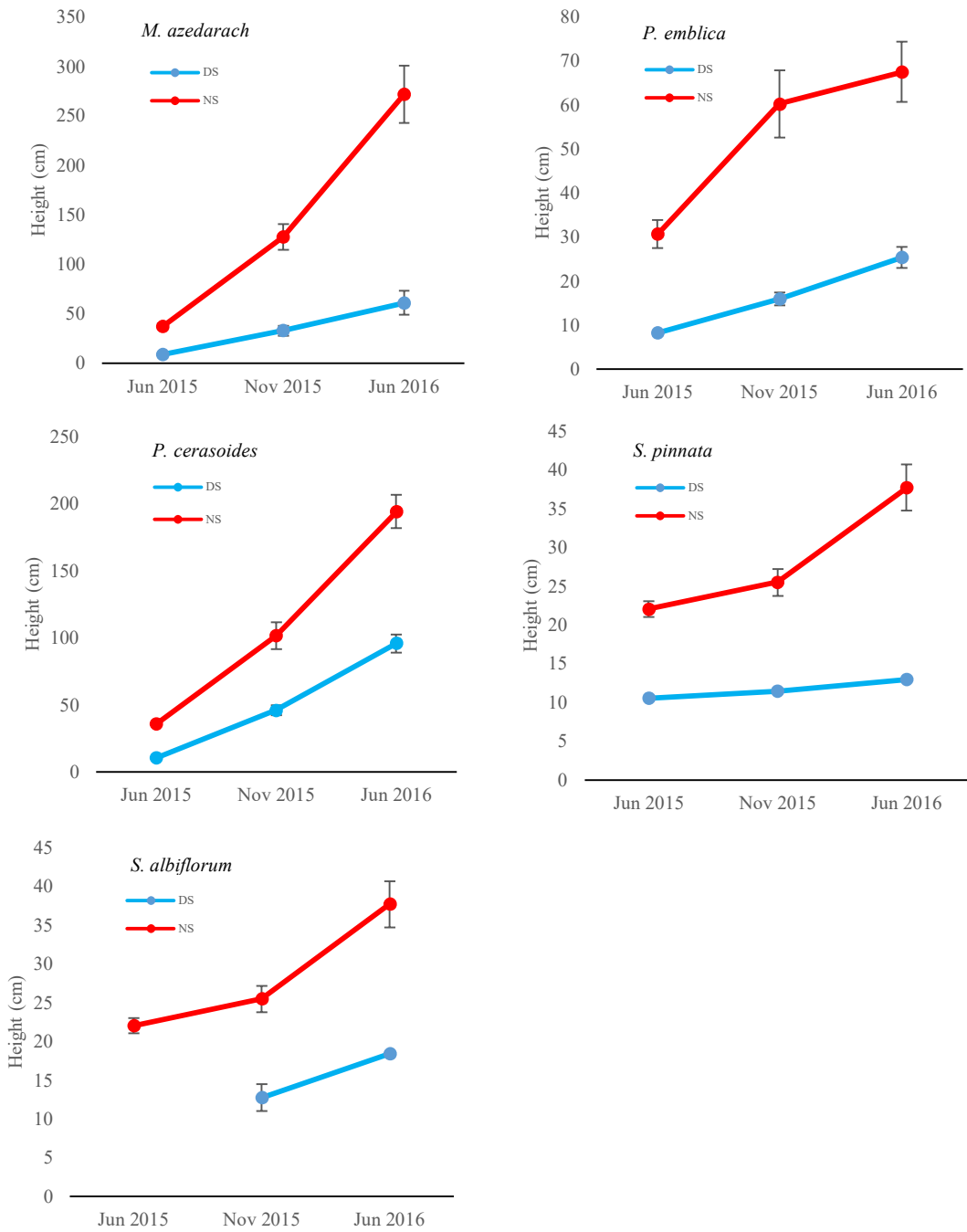
Figure 4.43 Continued.

Paired t-tests were performed, since each nursery raised seedling was planted next to direct seeded seedling. The mean height-RGR's of nursery-raised seedlings were significantly higher than those of direct-seeded seedlings in four studied species; *M. azedarach* (121.1 %/year higher, *t*-test, *p*=0.02, N=12), *P. cerasoides* (64.2 %/year higher, *t*-test, *p*=0.01, N=14), *D. longan* (130.4 %/year higher, *t*-test, *p*<0.01, N=8) and *M. garrettii* (71.6 %/year higher, *t*-test, *p*=0.04, N=9). In contrast, the mean height-RGR of *B. variegata* nursery-raised seedlings was 35.5 %/year lower than that of direct-seeded seedlings (*t*-test, *p*<0.01, N=15, Figure 4.44).
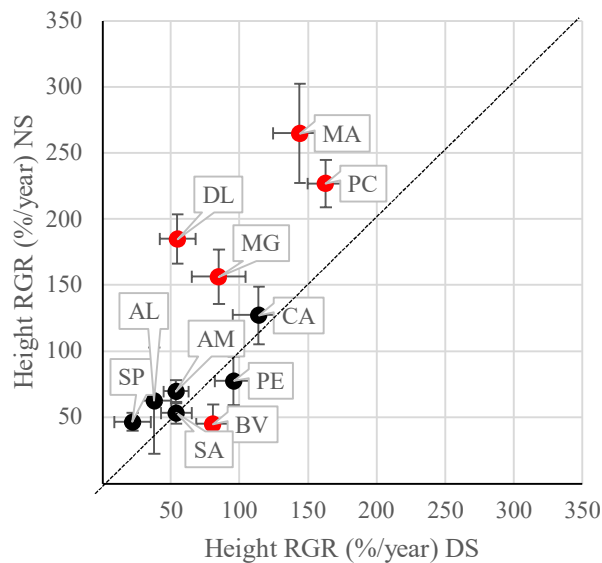
Figure 4.44 Comparison of mean (± SE) height relative growth rate (RGR) of 11 tree species seedlings, between nursery-raised seedlings (NS) and direct-seeded seedlings (DS). Red circles indicate significant difference between the two bars within each species (t-test, p < 0.05). Dashed line indicates axis X equals axis Y. AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

The mean CW-RGR's of nursery-raised seedlings were significant higher than those of directed-seeded seedlings for 6 species; *M. azedarach* (306.8 %/year higher, *t*-test, *p*<0.01, N=12), *A .lacucha* (280.3 %/year higher, *t*-test, *p*=0.03, N=9), *D. longan* (127.1 %/year higher, *t*-test, *p*=0.01, N=8), *P. emblica* (125.0 %/year higher, *t*-test, *p*=0.01, N=14) and *B. variegata* (31.0 %/year higher, *t*-test, *p*=0.04, N=15). *C. axillaris* was the only species for which CW-RGR was significantly lower (by 42.1 %/year) for nursery-raised seedlings (*t*-test, *p*=0.03, N=6 Figure 4.45).
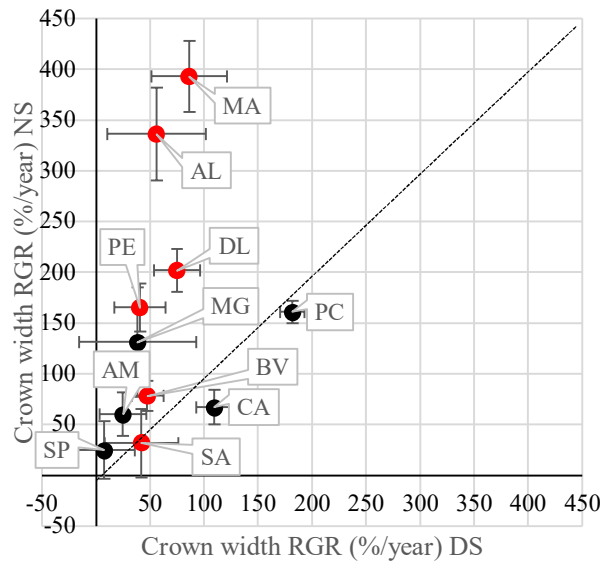
Figure 4.45 Comparison of mean (± SE) crown width relative growth rate (RGR) of 11 tree species seedlings, between nursery-raised seedlings (NS) and direct-seeded seedlings (DS). Red circles indicate significant difference between the two bars within each species (t-test, p < 0.05). Dashed line indicates axis X equals axis Y. AF=*A. fraxinifolius,* AM=*A. microsperma,* AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa,* GA=*G. arborea,* HG=*H. glabra,* HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

The mean RCD-RGR did not differ significantly between nursery-raised seedlings and direct-seeded seedlings, except for *M. azedarach*, for which nursery-raised seedlings achieved a mean RCD-RGR 235.5 %/year higher than that of direct-seeded seedlings (*t*-test, *p*<0.01, N=12, Figure 4.46).

105
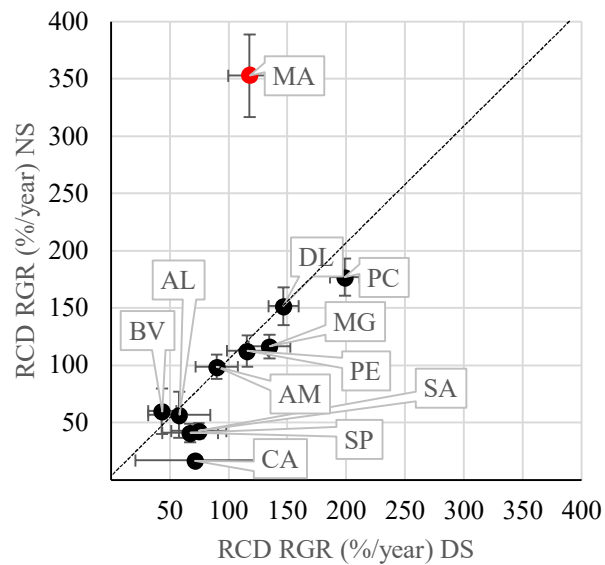
Figure 4.46 Comparison of mean (± SE) root collar diameter relative growth rate (RCD RGR) of 11 tree species seedlings, between nursery-raised seedlings (NS) and direct-seeded seedlings (DS). Red circles indicate significant difference between the two bars within each species (t-test, $p < 0.05$). Dashed line indicates axis X equals axis Y. AF=*A. fraxinifolius,* AM=*A. microsperma*, AK=*A. kurzii,* AL=*A. lacucha,* BV=*B. variegata,* CA=*C. axillaris,* DL=*D. longan,* DG=*D. glandulosa*, GA=*G. arborea,* HG=*H. glabra*, HD=*H. dulcis,* MA= *M. azedarach,* MG=*M. garrettii,* PE=*P. emblica,* PC=*P. cerasoides,* SP=*S. pinnata,* SA=*S. albiflorum.*

4.4 Hydrogel Experiment

Germination and dormancy of *A. fraxinifolius, A. lacucha, C. axillaris, G. arborea, P. emblica,* and *P. cerasoides* seeds were tested with mixture of hydrogel and forest soil in the nursery and the field. Statistical analyses were performed on the nursery data of all species and on the field data of *A. fraxinifolius, C. axillaris* and *P. emblica.* In the field, predators completely removed *A. lacucha, G. arborea* and *P. cerasoides* seeds (of all treatments) in replicate 1. Therefore, data from these species were insufficient for statistical analysis.

4.4.1 Seeds Germination and MLD

4.4.1.1 *Acrocarpus fraxinifolius*

Gel treatments did not significantly affect *A. fraxinifolius* seed germination or dormancy. Differences in mean percent germination and MLD were not significant, among all hydrogel treatments, both in the nursery and in the field (for germination ANOVA, $p=0.45$ and 0.07, Figure 4.47 a and b respectively and for dormancy ANOVA, $p=0.38$ and 0.75, Figure 4.47 c and d, respectively).

Figure 4.47 Mean (± SE) percent germination and MLD of *Acrocarpus fraxinifolius* a) germination in nursery, b) germination in field, c) MLD in nursery and d) MLD in field (3 replicates of 30 seeds each; control (forest soil); 10%, 20% and 30% hydrogel (by volume) mixed with forest soil; 100% (pure hydrogel, nursery only) and SH half layer of forest soil and hydrogel). See methods.

Consequently, to compare germination and dormancy between nursery and field conditions, data for all treatments (except 100% in the nursery) were combined for each location. Mean percent germination in field was significantly higher than in the nursey (by 64.0%). In contrast, dormancy showed no significantly differences (Table 4.14).

Table 4.14 Comparison of germination and median length of dormancy (MLD) of *Acrocarpus fraxinifolius* seeds between nursery and field (*t*-test on 15replicates; 30 seeds per replicate).

Parameters	Nursery		Field		*t*-test, *p*-value
	Mean	SE	Mean	SE	
Germination (%)	94.0	1.1	30.0	7.4	*p*<0.01
MLD (days)	32.6	0.0	29.5	6.6	0.63

4.4.1.2 *Choerospondias axillaris*

Differences in mean percent germination and MLD of *Choerospondias axillaris* were not significant, among all hydrogel treatments, both in the nursery and in the field, except that, germination in 100% hydrogel in the nursery was significantly lower than that of all other nursery treatments (germination ANOVA, *p*<0.01, Figure 4.48 a and *p*=0.88, Figure 4.468b and dormancy *p*=0.80 and 0.90, respectively, Figure 4.48 c and d).

Figure 4.48 Mean (± SE) percent germination and MLD of *Choerospondias axillaris* a) germination in nursery, b) germination in field, c) MLD in nursery and d) MLD in field (3 replicates of 30 seeds each; control (forest soil); 10%, 20% and 30% hydrogel (by volume) mixed with forest soil; 100% (pure hydrogel, nursery only) and SH half layer of forest soil and hydrogel). See methods. Column not sharing the same superscript letters are statistically different among treatments (mean differentiation using Turkey's HSD, α= 0.05).

Consequently, to compare germination and dormancy between nursery and field conditions, data for all treatments (except 100%) were combined for each location. Mean percent germination in nursery was significantly higher in the nursery than in field (by 16.6%) but dormancy was significantly prolonged in the nursery (by 140.5 days, Table 4.15).

Table 4.15 Comparison of germination and median length of dormancy (MLD) of *Choerospondias axillaris* seeds between nursery and field, (*t*-test on 15 replicates; 30 seeds per replicate).

Parameters	Nursery		Field		*t*-test, *p*-value
	Mean	SE	Mean	SE	
Germination (%)	52.4	2.2	35.8	2.5	*p*<0.01
MLD (days)	212.1	14.0	71.6	2.7	*p*<0.01

4.4.1.3 *Phyllanthus emblica*

Differences in mean percent germination and MLD of *Phyllanthus emblica* were not significant, among all hydrogel treatments, both in the nursery and in the field (germination ANOVA, p=0.47 and 0.69, respectively, Figure 4.49 a and b; dormancy p=0.30 and 0.91, respectively, Figure 4.49 c and d)
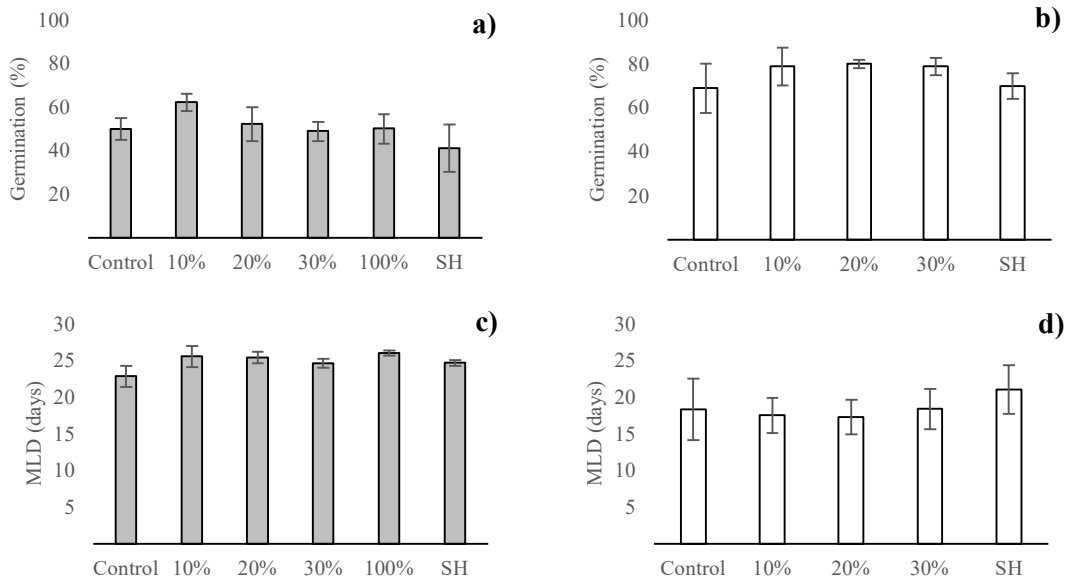
Figure 4.49 Mean (± SE) percent germination and MLD of *Phyllanthus emblica* a) germination in nursery, b) germination in field, c) MLD in nursery and d) MLD in field (3 replicates of 30 seeds each; control (forest soil); 10%, 20% and 30% hydrogel (by volume) mixed with forest soil; 100% (pure hydrogel, nursery only) and SH half layer of forest soil and hydrogel). See methods.

Consequently, to compare germination and dormancy between nursery and field conditions, data for all treatments (except 100%) were combined for each location. Mean percent germination was significantly higher (by 24.4%). and more rapid (by 6.1 days) in the field than in the nursery (Table 4.16).

Table 4.16 Comparison of germination and median length of dormancy (MLD) of *Phyllanthus emblica* seeds between nursery and field, (*t*-test on 15 replicates; 30 seeds per replicate).

Parameters	Nursery		Field		*t*-test, *p*-value
	Mean	SE	Mean	SE	
Germination (%)	50.9	3.2	75.3	3.0	*p*<0.01
MLD (days)	24.6	0.5	18.5	1.2	*p*<0.01

4.4.1.4 *Artocarpus lacucha*

As previously mentioned, only nursery data were analyzed statistically for this species. The 100% hydrogel treatment significantly decreased (by 64.5%), and delayed (by 6.5 days) germination, compared with all other treatments in the nursery (germination 22.6 ± 3.9%, ANOVA, $p<0.01$, Figure 4.50 a and dormancy 39.1 ± 1.0 days, ANOVA, $p<0.01$, Figure 4.50 c). In the field, mean percent germination ranged from 10 to 58.4% across (Figure 4.50 b) whilst MLD ranged from 22.0 days to 57.6 days.
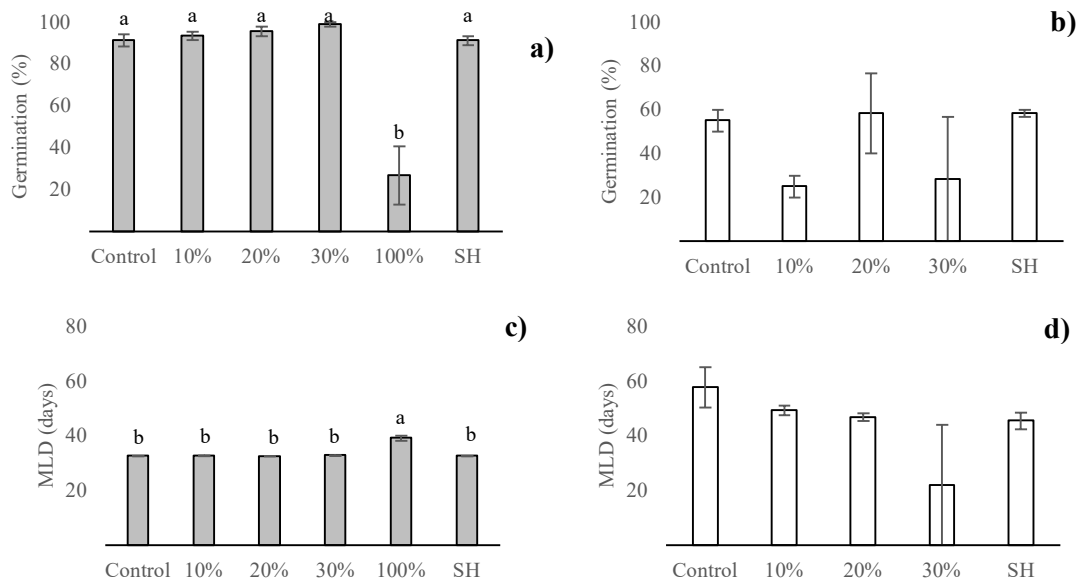
Figure 4.50 Mean (± SE) percent germination and MLD of *Artocarpus lacucha* a) germination in nursery, b) germination in field, c) MLD in nursery and d) MLD in field (3 replicates of 30 seeds each; control (forest soil); 10%, 20% and 30% hydrogel (by volume) mixed with forest soil; 100% (pure hydrogel, nursery only) and SH half layer of forest soil and hydrogel). See methods. Column not sharing the same superscript letters are statistically different among treatments (mean differentiation using Turkey's HSD, α= 0.05).

Germination of this species appeared to be higher (by 49.0%) and more rapid in the nursery (by 11.6 days) than in the field, but statistical analysis could not be performed to determine if this result was significant.

4.4.1.5 *Prunus cerasoides*

As previously mentioned, only nursery data were analyzed statistically for this species. In the nursery, differences in mean percent germination among treatments were not significant (ANOVA, *p*=0.05, Figure 4.51 a). However, the mean MLD of seeds, sown in 100% hydrogel, was slightly, but significantly, longer than that of seeds sown in 20% hydrogel (by 7.0 days) differences compared with other treatments were insignificant (ANOVA, *p*=0.03, Figure 4.51 c). In the field, mean germination ranged from 10.0 to 50% across treatments (Figure 4.51 b), whilst mean MLD ranged from 25.3 to 36.9 days (Figure 4.51 d).
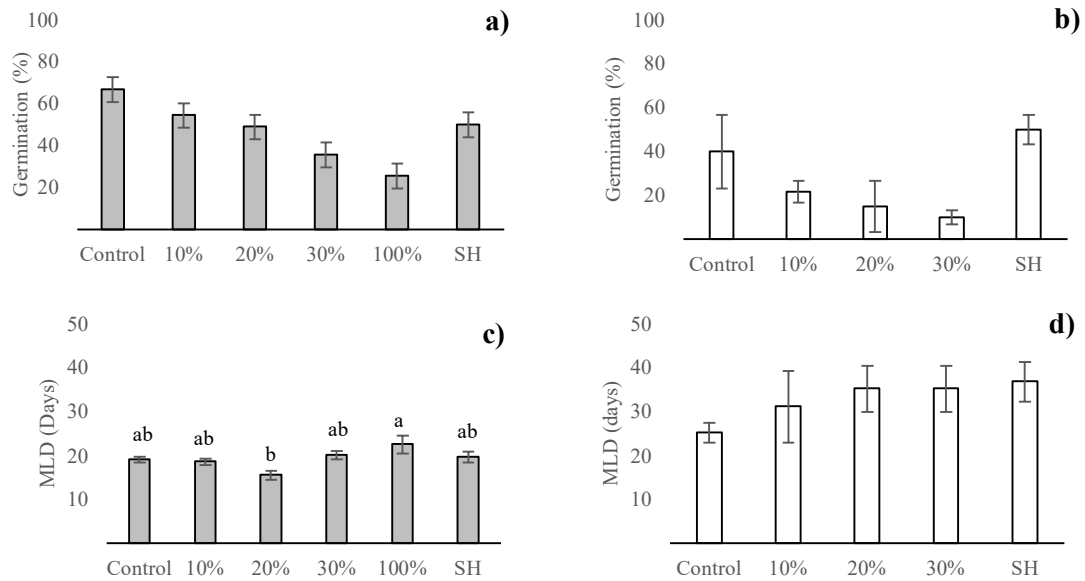
Figure 4.51 Mean (± SE) percent germination and MLD of *Prunus cerasoides* a) germination in nursery, b) germination in field, c) MLD in nursery and d) MLD in field (3 replicates of 30 seeds each; control (forest soil); 10%, 20% and 30% hydrogel (by volume) mixed with forest soil; 100% (pure hydrogel, nursery only) and SH half layer of forest soil and hydrogel). See methods. Column not sharing the same superscript letters are statistically different among treatments (mean differentiation using Turkey's HSD, α= 0.05).

It appeared that germination was substantially higher (by 23.8%) and more rapid (by 14.2 days) in the nursery than in the field, but it was not possible to confirm the significance of this result statistically.

4.4.1.6 *Gmelina arborea*

Germination of *G. arborea* seeds was very low (generally less than 10%) and zero in 100% hydrogel. In the nursery differences in mean percent germination and MLD were not significant (ANOVA, *p*=0.65, Figure 4.50 a; ANOVA, *p*=0.60, Figure 4.52 c). In the field, mean percent germination ranged from 3.4 to 5% across treatments (Figure 4.52 b). Whereas mean dormancy ranged from 8.5 to 17.0 days (Figure 4.52 d).

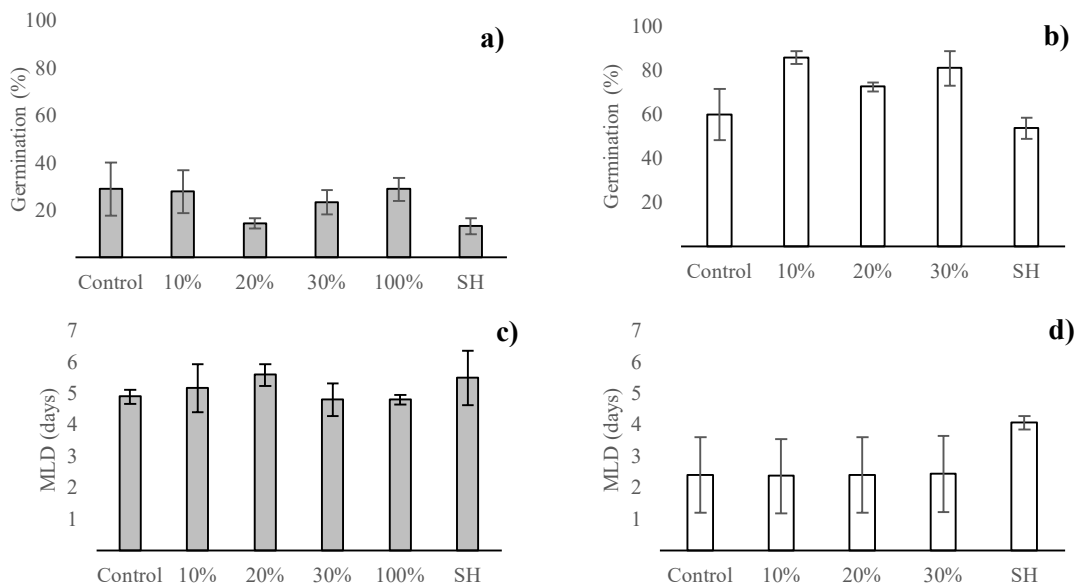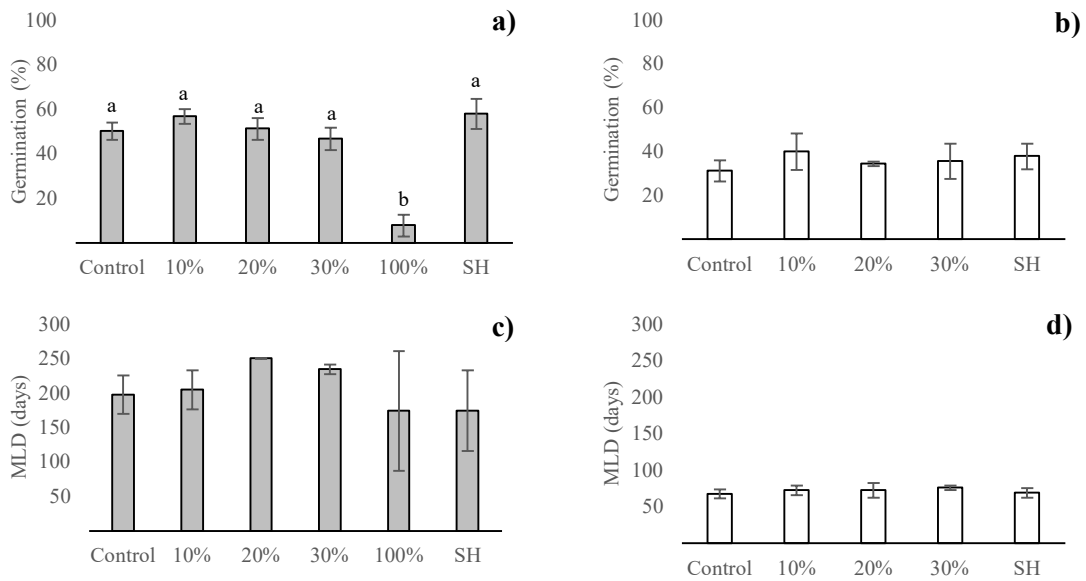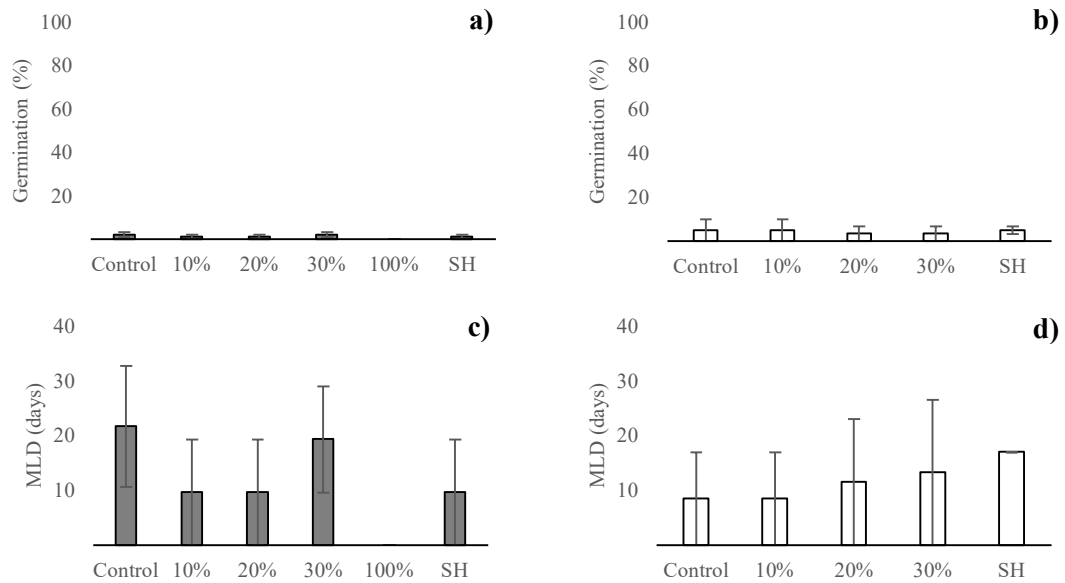**Figure 4.52** Mean (± SE) percent germination and MLD of *Gmelina arborea* a) germination in nursery, b) germination in field, c) MLD in nursery and d) MLD in field (3 replicates of 30 seeds each; control (forest soil); 10%, 20% and 30% hydrogel (by volume) mixed with forest soil; 100% (pure hydrogel, nursery only) and SH half layer of forest soil and hydrogel). See methods.

It appeared that germination may have been slightly higher (by 2.8%) and slightly more rapid (by 2.3 days) in the field than in the nursery, but it was not possible to confirm the significance of this result statistically.

4.4.2 Seedling Survival

Gel treatments did not significantly affect *A. fraxinifolius* and *P. emblica* seedling survival (defined as the number of seedlings at the monitoring time, as a percentage of the number of seedlings that germinated) (Table 4.17). In contrast, *C. axillaris* seedlings survived significantly better in 20% hydrogel, compared with 30% hydrogel and the SH treatment (43.1% and 42.1%, respectively).

In general, it appeared that gel treatments may have increased survival of *P. cerasoides* seedlings, but decreased that of *A. lacucha*, but it was not possible to prove this statistically. So few seedlings of *G. arborea* germinated that calculation of mean survival rates became meaningless.

The 30% hydrogel treatment substantially reduced seedling survival of *A. lacucha* from 81.1% (control) to 38.3%.

No seedlings of *G. arborea* survived the 20% and 30% hydrogel treatments. All hydrogel treatments appeared to substantially increase survival of *P. cerasoides* seedlings (compared with the control) except the soil/hydrogel layered treatment (Table 4.17).

Table 4.17 Percent seedling survival in the field over 231 days (09/12/15 to 27/07/16) after 1st dry season of tested species with various hydrogel (H) treatments applied (3 replicates of 30 seeds). SH indicates a half layer of soil and hydrogel.

species	Control		10% H		20% H		30% H		SH		p-value
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
Acrocarpus fraxinifolius	49.0	7.6	49.1	5.0	29.9	2.7	46.0	4.0	32.0	8.4	0.11
Choerospondias axillaris	42.2[ab]	9.3	35.8[ab]	8.0	66.5[a]	6.2	23.4[b]	3.5	24.4[b]	6.7	0.01
Phyllanthus emblica	81.1	8.5	86.9	4.7	73.8	4.5	82.8	6.8	66.3	5.2	0.21
Artocarpus lacucha*	81.1	7.8	61.2	5.6	70.5	12.2	38.3	38.3	51.8	12.9	-
Prunus cerasoides*	49.2	8.0	87.5	12.5	87.5	12.5	62.5	37.5	42.8	4.3	-

- An asterisk (*) above species indicates mean percent calculated from 2 replicates.
- Mean values of the first three species, not sharing the same superscripts are statistically different (Turkey's HSD, α=0.05).

4.4.3 Seedling Yield

Gel treatments did not significantly affect seedling yield (defined as the number of seedlings at the monitoring time, as a percentage of the number of seed sown) of tested species (Table 4.18).

Table 4.18 Percent seedling yield in the field over 408 days (15/06/15 to 27/07/16) after passed 1st dry season of tested species in different amount of hydrogel (H) applied in sowing media, testing in field with 3 replicates of 30 seeds. SH indicates a half layer of soil and hydrogel.

species	Control		10% H	20% H	30% H	SH	p-value
	Mean	SE	Mean				

CHAPTER 5

Discussion and Conclusion

The chapter discusses the extent to which the results, generated by this research, supports or refutes the objectives of this study which were; i) to determine optimal seed storage condition of native tree species, ii) to compare direct seeding success between seeds sown at the seed collection time and those stored until the optimum direct seeding season, iii) to compare direct seeding with conventional tree planting, iv) to develop treatments to improve direct seeding and v) to contribute towards applications for automated forest restoration. The last topic was to address development of applications for up-to-date forest restoration techniques.

5.1 Determining Optimal Seed Storage Condition of Native Tree Species

Seed Storage Behaviour

The high prevalence orthodox seeds amongst the tree species tested in this study, reflected the global consensus as to the predominance of this storage behaviour amongst woody plants around the world. Ten out of 17 species were orthodox (58.8%); 11.8% were intermediate and 29.4% were recalcitrant. A global study of trees and shrubs of 886 species from 93 families, across 15 vegetation zones reported that 80.1% were orthodox, 2.3% intermediate and 17.6% recalcitrant (Tweddle et al., 2003). In tropical evergreen rain forest (178 species, 39 families) the percentages reported were 50.6% orthodox, 2.8% intermediate and 46.6 recalcitrant (very similar to the percentages in my study) whilst in tropical deciduous forest (178 species, 39 families) they were 88.9% orthodox, 2.2% intermediate and 8.9 recalcitrant (Tweddle et al., 2003).

Considering individual species, I compare my results to those of 3 main data sources; i) Royal Botanic Gardens Kew (2017) ii) Thapliyal and Phartyal (2005) and iii) Pakkad (2005). *A. microsperma* was ranked as orthodox, with an initial seed moisture content of only 7%. Seeds of this species survived well under sub-zero temperatures without loss of viability, but such low temperatures were not necessary, since seeds could be stored for at least 12 months at normal seed moisture content and at ambient temperature. Seeds of other species in the same genus behave similarly. Both *A. abrosperma* and *A. pavonia* are classified as orthodox (Royal Botanic Gardens Kew, 2017).

B. variegata seeds survived without viability loss after being stored at -20 °C for 1 month. Furthermore, this species could be stored for at least 12 months at 5% MC in a refrigerator, whereas seed stored at normal moisture content at room temperature totally lost viability after 6 months' storage. Most other *Bauhinia* species have also been classified as orthodox (e.g. *B. aurantiaca*, *B. binate*, *B. galpini*, *B. galpinii*, *B. trichosepala* and *B. urbaniana*) with germination reduced by up to 23% after one year storage at room temperature (Thapliyal and Phartyal, 2005).

P. emblica totally lost viability after 12 months' refrigerated storage at both normal and reduced seed moisture contents. Conversely, it survived well at room temperature. So, this species was classified as orthodox, the same as reported for other species in the same genus (e.g. *P. amarus, P. casticum, P cochinchinensis, P. dinteri, P. engleri and P. maderaspatensis* (Royal Botanic Gardens Kew, 2017). Baseline germination in my study (38.7%) was much higher than that reported by a previous study (2%) (Thapliyal and Phartyal, 2005) and similarly after one year storage (24.4% vs 2%).

P. cerasoides could be stored in a refrigerator without viability loss for at least 12 months at either normal or reduced seed moisture content. This species was sensitive to storage a room temperature, which caused viability loss after 6 months' storage. A previous study suggested storing dry seed at 5% °C could maintain seed viability for at least six months and recommended that seeds should be collected early in the fruiting period (Pakkad, 2005).

Melia azedarach was classified in this study as orthodox, which is the same as for other species in the same genus (e.g. *M. azedarach*, *M. azedarach* var. *australasica*, *M. birmanica* and *M. volkensii* (Royal Botanic Gardens Kew, 2017)). This study recommended seed stored at normal moisture content in a refrigerator could maintain their viability for least one year. Another study found that storing dry seeds at room temperature maintained viability for six months and recommended that seeds should be collected at early fruiting period (Pakkad, 2005).

A. fraxinifolius and *D. glandulosa* were both classified as intermediate due to significant loss of seed viability upon drying and chilling (Hong and Ellis, 1996). Species of *Diospyros* vary in their seed storage behaviour. For example, *D. abyssinica* subsp. *abyssinica, D. bussei, D. fischeri, D. humbertiana* and *D. kirkii* are orthodox, whereas *D. philippensis* and *D. pilosanthera* are recalcitrant. *D. kaki* and *D. lotus* are probably intermediate while, D. *digyna, D. embryopteris* and *D. virginiana* are of uncertain classification (Royal Botanic Gardens Kew, 2017).

Seeds of five species were classified as recalcitrant; *A. lacucha*, *C. tribuloides, D. longan*, *H. glabra* and *S. albiflorum*. Seed in this group of species were all very sensitive to desiccation (Hong and Ellis, 1996). The result for *A. lacucha* agrees with previously reported findings for many congeneric species. Royal Botanic Gardens Kew (2017) list *A. altilis, A. blancoi, A. camansi, A. champeden, A. communis, A. heterophyllus, A. integra* and including *A. lacucha* as recalcitrant. Initial seed moisture content of this species is high (46.4%), similar to other recalcitrant species. Percent germination in my study was much higher (92%) than that reported in other studies.

D. longan seeds also contained high initial moisture content (43.4%) but presented low initial percent germination (8.7%). The seed storage behaviour and moisture content found in my study was similar to those reported by previous researchers (Recalcitrant, MC=46%, Royal Botanic Gardens Kew, 2017).

The Royal Botanic Gardens Kew (2017) list many *Syzygium* species as recalcitrant (e.g. *S. cordatum, S. guineense, S. maire, S. paniculatum* and including *S. albiflorum*). Seeds contained initially relatively high initial moisture content (35.7%) and had moderate (49.3%) but seeds quickly lost viability when dried to 10% MC.

Seed Storage Recommendations

Seeds of orthodox and intermediate species mostly survived without significant viability loss for 12 months under various storage conditions. When storage treatments had no significant effect on per cent germination, the cheapest and most convenient techniques are recommended (Table 5.1). Seeds of *A. fraxinifolius, A. microsperma, P. emblica,* and *S. pinnata* could be successfully stored at normal moisture content and at ambient temperature without viability loss for 12 months. Seeds of 7 species; *A. kurzii, C. axillaris, G. arborea, H. dulcis, M. garrettii M. azedarach,* and *P. cerasoides* could be stored at normal moisture content in a refrigerator for up to 12 months. *B. variegata* was the only species which required both drying and refrigeration.

Table 5.1 Storage techniques recommendation for 18 tree species, NMC= normal moisture content, 5% MC = seeds were reduced moisture content to 5 % MC, A and R = Ambient and refrigerator temperatures.

Species	Seed collection month	No. of months to June	Recommended techniques	Longevity** (months)
Orthodox				
Adenanthera microsperma	February	4	NMC A	12
Alangium kurzii	July	11	NMC R	6
Bauhinia variegata	May	1	5% MC R	12
Choerospondias axillaris	July	11	NMC R	3
Gmelina arborea	May	1	NMC R	12
Hovenia dulcis	February	4	NMC R	12
Manglietia garrettii	October	8	NMC R	12
Melia azedarach	January	5	NMC R	12
Phyllanthus emblica	January	5	NMC A	12
Prunus cerasoides	April	2	NMC R	12
Spondias pinnata*	March	3	NMC A	12
Intermediate				
Acrocarpus fraxinifolius	April	2	NMC A	12
Diospyros glandulosa	November	7		
Recalcitrant				
Artocarpus lacucha	June	-	Cannot be stored. Direct seeding or sow in nursery as soon as possible after seed collection.	
Castanopsis tribuloides	October	8		
Dimocarpus longan	October	8		
Horsfieldia glabra	May	1		
Syzygium albiflorum	June	-		

*   Seed storage behaviour not tested in this study.

** Max no. of months' storage with no significant reduction in % germination cf. % germination at seed collection time.

Seed Biology

Seed Germination

The germination percentages of 17 native tree species in the present study were categorized as low (<30 %), intermediate (30-60%) or high (>60 %) (see Table 4.1). The low-germination group comprised *Dimocarpus longan*, *Diospyros glandulosa*, *Gmelina arborea* and *Spondias pinnata*. Previous data in FORRU's database (unpublished) were similar for several species e.g. *D. glandulosa* (3%), *G. arborea* (11.1%) and *S. pinnata* (26.7%), all lower than 30%. *G. arborea* germinated the least in this study, only 6.0%, similar to previous data (11.1%), although FORRU found that germination could be dramatically increased when seeds were soaked in water for 2 nights (95.9%).

D. glandulosa exhibited low germination in the nursey. Moreover, seedlings of this species became infected with a disease that damaged the roots, stem and leave damages, consequently seedlings died at early stage (Figure 5.1).

Figure 5.1 Seedlings of *D. glandulosa*, affected by damping off disease.

In high germinated group, *Artocarpus lacucha* germinated the most in this study, 92.0%, followed by *Bauhinia variegata* 85%. *Bauhinia variegata* also successfully germinated 96 % when sowed in moist filter paper or sand (Thapliyal and Phartyal, 2005).

Seeds scarification increased the percent germination of *Acrocarpus fraxinifolius* but had no effect on germination of *Adenanthera microsperma.* In a previous experiment, scarification reduced germination of *A. microsperma* by 41% (FORRU, unpublished data). Furthermore, scarification significantly shortened dormancy of both species. Dormancy of *A. fraxinifolius* and *A. microsperma* seeds was reduced by 99 days and 14 days respectively. This was similar to previously reports that dormancy of *A. fraxinifolius* and *A. microsperma* were shortened by 153 days and 29 days respectively (FORRU, unpublished data). Consequently, scarification is highly recommended for these two species.

Seed Dormancy

Dormancy in the current study ranged from 8 days for *B. variegata* to 244 days for *C. axillaris*. *B. variegata* exhibited rapid seedling emerging with high percent germination. However, the leaves and stems of this species were seriously damaged by insects (personal observation, Figure 5.2), such that most seedlings died two weeks after germination.

145

Figure 5.2 Seedlings of *B. variegata* attacked by insects developing secondary fungal infections.

C. axillaris exhibited the longest dormancy (244 days), similar to Pakkad's (2005) findings of 43 days to 70 days for seeds collected very early or very late in the fruiting period respectively. *C. axillaris* germinated unevenly in this study. A few seedlings emerged after sowing for a month with more emerging after eight months, which resulted in the long median dormancy figure.

P. emblica is categorized as having prolonged dormancy: 107 days. FORRU (unpublished) showed that dormancy was shortened when seeds were sown under full sunlight (MLD 70 days) compared with sowing under shade (MLD 112 days). In addition, seed scarification reduced dormancy (scarification 31 days *vs* control 72 days) and increased germination (scarification 84% vs control 67%) (FORRU, unpublished data).

5.2 Comparing Direct Seeding Success between Seeds Sown at the Seed Collection Time and those Stored until the Optimum Direct Seeding Season

Germination

Germination of most species did not differ significantly between the nursey and the field when sown at collection time except that *A. fraxinifolius, A. lacucha* and *C. axillaris* germinated significantly better in the nursery. In the nursery, seeds were sown under shade with sufficient moisture, whereas conditions in the field were, warmer, lighter and more exposed.

Similar results were obtained after storage until the beginning of the rainy season. For most species, per cent germination did not significantly differ between the nursery and the field. Three exceptions were *M. azedarach, M. garrettii* and *P. emblica* which germinated significantly better in the field than in the nursery. Seeds of *H. glabra* and *A. lacucha* totally lost viability when stored even for very short periods. These two species were classified as recalcitrant in the present study, as they were sensitive to desiccation (Hong and Ellis, 1996). Storage of any duration (even less than one month before sowing time) lead to loss of moisture content, subsequently seed death.

Comparing germination between the two sowing times (immediate and after storage), found no significant differences except for *H. glabra*, which germinated only when sown immediately. *A. lacucha* seeds germinated significantly at collection time than after storage. These 2 recalcitrant species could not be stored until the optimum sowing time. Consequently, they should be sown immediately after seed collection. In another study, Tunjai (2005) failed to germinate *A. lacucha* seeds under all conditions in her experiment; with/without pre-treatment or weed control.

Dormancy

Three species took significantly longer to germinate in the field than in the nursery, when sown at collection time rather than after storage: *A. microsperma* (AM)*, M. azedarach* (MT) and *S. pinnata* (SP). Collection times of these species fell outside of the rainy season (sowing date: AM 25th February, MT 6th January and SP 1st April), but the the median date of germination of these species occurred during rainy season (AM 10th May, MT 3rd

147

May and SP 17th July). In the field, moisture supply was sporadic unlike in the nursery, where water was applied daily.

In contrast, dormancy of *B. variegata* seeds was shorter in the field, when sown at collection time compared with longer dormancy in the field than in the nursery after storage. Seeds of *B. variegata* were sown on 21st May which was already in the rainy season. Water, therefore was not a limiting factor. This species may require sunlight to support germination.

Dormancy of seeds sown at collection time was significant longer than for stored seeds in the field for: *A. microsperma*, *H. glabra, H. dulcis*, *M. azedarach*, *P. emblica, P. cerasoides* and *S. pinnata*. These species were firstly sown out of rainy season, expect for *H. glabra* which was sown in May. The median germination date of all these species occurred in the rainy season. These species require sufficient water to germinate.

Seedling Survival and Seedling Yield

In general, percent seedling survival and seedling yield (defined as percentage of survival seedling from total seed sown over one year), were not significantly different between the two sowing periods. *B. variegata* achieved the highest percent survival (69.7%) and seedling yield (60.7%). This species sown at collection time on 21st May had the highest percent germination (88.7%) and shortest dormancy (3.8 days). Seed size was 0.275 g which categorized the species as intermediate seed size (Doust, et al., 2006). Previous studies have shown that large or intermediate-sized seeds result in higher seedling survival (Tunjai and Elliott. 2012). *P. emblica* also exhibited high percent survival (51.1%) and had moderate seedling yield (22.1%) according to Tunjai and Elliott (2012). However, seed size of this species was small (0.024), the yield was relatively high (22.1%) compare to other studied species. *G. arborea* and *H. dulcis* had very low (less than 4%) survival while, *A. fraxinifolius* seedlings all died in the field. Small seed size often seems to predict failure of direct seeding (Tunjai and Elliott. 2012; Kuaraksa and Elliott. 2013). In addition, seedlings from small seeds had high risk in seed infection. For example, Kuaraksa and Elliott (2013) reported 90% mortality of *Ficus* spp. seedlings, due to damping-off disease. However, in this study, no relationships were found between seed size and seed germination, dormancy, seedling yield and growth. *G. arborea* and *H. dulcis* failed to establish by direct seeding in this study. In contrast, Tunjai (2005) reported very

high percent survival *G. arborea* (more than 90%) after 2 years of monitoring and Pakkad (2005) reported similar results from *H. dulcis*, suggesting both species should be recommended for direct seeding. *A. lacucha,* a recalcitrant species, was only the species for which percent yield from immediately sown seeds was significant higher than for those from stored seeds.

Seedling Growth

Sowing time did not affect seedling growth. Differences in seedling height, crown width (CW) and root collar diameter (RCD) between immediately sown and stored seeds were not significant within species 1 year after sowing. *P. cerasoides* seedlings were the tallest (87.4 cm) and achieved the greatest mean crown expansion, followed by *M. azedarach* (46.9 cm) and *B. variegata* (30.4 cm). *P. cerasoides* seedlings also achieved the highest rate of crown expansion and highest root collar diameter RGR. Tunjai. 2005 reported similar results for direct sown *P. cerasoides* and *M. azedarach* seedlings. *P. cerasoides* seedlings grew to 80 cm tall, whilst those of *M. azedarach* seedlings grew to 120 cm tall after one year. *P. cerasoides* and *M. azedarach* are remarkably fast-growing species, which flower and fruit at a young age (2-3 years) and attract seed dispersing animals. FORRU (2006) recommended these two species as framework species for forest restoration. Elliott et al. (2013) recommend planting out seedlings when they are 30-50 cm tall. Therefore, these species achieve the recommended seedling size for forest restoration within a year after direct seeding. The remaining species grew to less than 30 cm tall. *A. fraxinifolius* seedlings were the smallest, only 4.3 cm tall. Consequently, this species is not recommended for direct seeding. In contrast, FORRU (2006) reported excellent results of this species with conventional tree planting and it was therefore recommended as a framework species, if planted as appropriately-sized saplings.

Relative Species Performance Indices (RSPI's)

RSPI's were calculated based on three models. First model followed Tunjai and Elliott (2012), which combined percent establishment (percent yield used in this study) and absolute seedling height at time X from sowing/planting. Relationships between height and crown width and root collar diameter were strong, so seedling height alone could be used to represent seedling size. *B. variegata* performed the best using this height-based follow by *P. cerasoides* and *M. azedarach* respectively. *G. arborea* performed the worst.

A second model substituted RGR height instead of absolute height, since seedlings had different initial heights after emerging, which resulted in different final heights after one year. RGR-height was strongly correlated with RGR's for crown width and root collar diameter, so RGR height was used as the most convenient parameter, since errors in height measurements are lower than for the other two parameters. This model produced very similar results as the previous model. *B. variegata* performed the best, followed by *P. cerasoides* and *M. azedarach,* whereas, *G. arborea* performed the worst.

The last model combined a growth index, calculated on tree volume, equally weight with percent yield. This method resulted in slightly different species ranking order. *P. cerasoides* replaced *B. variegata* was the highest performing species with an RSPI of 64.7. *P. cerasoides* exhibited the highest growth and had a moderate seedling yield (17%). However, other species were mostly ranked similarly as with the previous two methods. In this study suggested the second method, calculation model with height RGR, was the practical method.

The present study recommended *P. cerasoides* for direct seeding. However, acquiring sufficient seeds to produce enough seedlings must be considered. Tunjai (2005) also reported excellent results of direct seeding with *P. cerasoides*. *B. variegata* was species had the highest seedling yield but had lower growth performance. Therefore, this species is recommended for place requires high yield but slow growth. The suitability species type of direct seeding could be classified into four group depend on purposes of selection; i) good establishment and rapid growth, ii) poor establishment and rapid growth, iii) good establishment and sow growth and iv) poor establishment and slow growth (Doust, et al., 2008). The last group is unfavorable for direct seeding method.

Sowing times were previously tested on degraded sites in the wet tropical region of north east Queensland, Australian. This research found that sowing time had small effects on seedlings establishment (Doust et al., 2008). Similarly, result was found in this study, which sowing times (sown at collection time and stored and sown at the beginning of rainy season) were not effect to percent germination, seedling establishment and seedling growth.

5.3 Comparing Direct Seeding with Conventional Tree Planting

Kuaraksa and Elliott (2013) reported lower success with direct-seeding, compared with conventional tree planting, particularly for small-seeded tree species. High seed availability, large seed size (more than 5 g), high viability and storage potential, high germination and growth rate, low sensitivity to competition and broad tolerance range of shade all contribute to the successfulness of direct seeding (Doust et al., 2008). This study also found lower success of direct-seeded seedlings, compared with nursery-raised seedlings (averaged across species) one year after planting. For example mean heights of direct-seeded seedlings were close to the initial planting heights of nursery-raised seedlings (NS) of 7 species. However, 3 species had seedling height about twice as tall as the initial height of nursery-raised seedlings; *M. garrettii*, *M. azedarach* and *P. cerasoides*.

Nursery raised-seedling showed generally high percent seedling yield (average 40.9%). *M. azedarach, A. microsperma* and *D. longan* seedlings survived well in the field (72.7, 78.6 % and 79.7%, respectively). *M. azedarach* also had the highest growth performance, and consequently the highest species performance index (SI= 80.9). *M. azedarach* is a fast-growing species, with high survival rate (90%) two years after planting. It produces flowers at 4 years of age and seeds at 5 years. Consequently, FORRU (2006) strongly recommend it as a framework species for restoring degraded sites in northern Thailand.

5.4 Developing Treatments to Improve Direct Seeding

Hydrogel

Polyacrylamide gel or hydrogel is a soil conditioner that has been widely used in agriculture, due to its high water absorbance (Green and Stott, 2001). However, the use of gel for forest tree species is poorly understood (Landis and Haase, 2012). The present study showed that percent germination was unaffected by the hydrogel treatments, except that 100% hydrogel significantly reduced percent germination of *A. lacucha* and *P. cerasoides*. Hydrogel provides a consistent supply of moisture to seeds during germination, which usually results in increased percent germination and shortened dormancy (Duangpatra, 2010). However, it appears that a high proportion (100%) of hydrogel, restricts oxygen supply to the seeds which probably accounts for the decreased germination mentioned above.

In the field, percent germination was not significantly different among treatments. Seeds of *A. fraxinifolius*, *C. axillaris* and *P. emblica* were lost due to seed predation. In the area, used for my study, Naruangsri and Tiansawat (2016) observed rodent seed predators. Although, this study had already designed an experiment to prevent seed predation by burial seed (Doust et al., 2006; Doust et al., 2008). This burial technique may not be efficiency enough and should be considered other method to reduce seed predation effects such as testing on rodent repellent.

In general, seedling yield of studied species were not significantly different among testing periods (after first rainy season (December 2015) and beginning of second rainy season July 2016), except *C. axillaris* in the treatment of 10% hydrogel and layer of gel and soil of which yield significantly reduced when passed the drought period. The result in this study was contrast with Chirino and Vilagrosa (2011) which found gel significantly support seedling during drought period.

Differences in relative growth rates (height, crown and root collar diameter) among species likely were not significant. Crown width RGR of *A. franxinifolius* and *C. axillaris* exhibited negative values in every treatment. This may be due to that fact that these two species are deciduous (Gardner et al., 2000).

Fertilizers

Nutrients are vital for plant growth and development. Plants normally uptake important nutrients from planting media (Jacobs and Landis, 2014). Nutrients are important, particularly during the early stages of seedling development. Fertilizers are therefore often applied to seedlings grown in nurseries and after out-planting (FORRU, 2006; Hasse et al., 2014). Seedlings normally receive 0.3 g of slow release fertilizer during nursery stage (FORRU, 2006). In the current study, the amount of fertilizer could be reduced by half portion of these species; *A. franxinifolius*, *A. microsperma*, *A. lacucha*, *P. emblica*, *P. cerasoides* and *S. albiflora* due to all these species presented no significantly different in mean relative growth rate (height, crown width and root collar diameter).

Seedlings of almost all species failed to grow to the standard minimum size for planting out (30 cm) 187 days after potting. The exception was *P. cerasoides* which grew taller than 30 cm 112 days after potting. FORRU (2006) recommended out-planting size at 30-50 cm. This is an only species could be planted at 187 days. *P. cerasoides* exhibited high success with both conventional tree planting and direct seeding, with high performance both in the nursery and in the field, during my study. Therefore, this species is strongly recommend for restoration of degraded forest sites in northern Thailand.

In addition, fertilizer treatments had no significant effects on seedling biomass and root: shoot ratio of the study species. New develop fertilizer, NANOTECH, with new coating technique can be replaced the conventional fertilizer, Osmocote, by applying only half portion (0.15 g NANOTECH fertilizer).

5.5 Applications for Automated Forest Restoration

Automated forest restoration (AFR), using drones to drop seeds in "bombs" or pellets is now actively being explored to implement forest restoration on expansive, remote areas of degraded land, particularly to meet the requirements of ambitious large-scale reforestation target set by the Bonn Challenge and the New York Declaration. However, the development of such techniques requires knowledge gaps to be filled. Biocarbon Engineering is a company, currently developing various technologies for AFR such as; i) mapping technology with accurate surface topology and slope angles, surface composition and obstructions, vegetative indices and soil type and moisture, ii) a aerial seeding system with less plating time less than 6 second, possible to plant in different soil type and various plant species, iii) biodegradable seedpods, the degradation time is suitable with the seed germination rate. The pods can carry multiple seed types and sizes, iv) monitoring system with accurate area analysis tools and v) data collection system for further plating evaluation (Biocarbon Engineering, 2017). The company is aiming to apply such AFR technologies for commercial purposes and requires high investment costs for initial star-up.

Species selection should firstly be addressed in order to understand AFR. In my study, species were selected that were considered to be suitable for direct seeding. My study showed that *P. cerasoides* performed the best and should be considered as highly suitable for AFR, followed by *B. variegata, M. azedarach* and *P. emblica.* Previous studies have shown that larger seeds tend to be more suitable for direct seeding than small ones (Doust et al., 2006; Doust et al., 2008; Tunjai and Elliott, 2012). Therefore, seed bomb/pellet technologies should be aimed at accommodating large seed sizes.

My study showed that orthodox seed can be sown either shortly after collection or stored and then sown at the start of the rainy season, without significant reduction in seed germination and/or seedling survival and growth. In contrast, recalcitrant seeds must be sown soon after seed collection in order to maintain seed viability. However, even orthodox seeds require proper storage conditions. So, further work on storage of other orthodox species must be considered.

Seed bombs or seed pellets effective function as "redesigned fruits" or dispersal units when employed in aerial seeding. The design of seed bombs/pellets should take into

account soil hardness and texture, topography, seed characteristic and the constituents of the media of the pelleting materials or contained within the seed bombs. Seed projectiles should at least remain where they are dropped (for accurate spacing between seeding sites). Bombs can be designed with a sharp point to anchor the seeds in placed, whereas spherical pellets tend to roll around and accumulate in the lowest points of the landscape.

Both seed bomb and pellet materials should not inhibit seed germination and seedling growth. Seed bomb materials must degradable according to the germination rate of the seeds within (Biocarbon Engineering, 2017). The essential point is that the projectile materials (whether bomb or pellet) must not inhibit seed germination and/or seedling growth.

Media within bombs should contain soil (preferably from the original forest type) as a source of symbiotic microbes, essential for tree growth (mycorrhizal fungi, nitrogen fixing bacterial etc.), fertilizers, hydrogel and rodent repellents. In my study I observed seed predation only in some plots or the hydrogel experiment. However, Naruangsri and Tiansawat (2016) reported that rodents are major seed predators where my study was located and other authors have reported similar results in other areas (Birkedal et al., 2009; Castro et al., 2015; Hau, 1997; Hau, 1999). So, further experiments should address the issue of seed predation prevention, by testing organic or chemical rodent repellents. Hüttermann et al. (1999) found that hydrogel was useful for moisture control on commercial tree seedlings in nurseries. However, my study found that hydrogel was of no significant use on native tree species seedlings for forest restoration in the field and on seed germination in the nursery. In addition, hydrogel did not reduce the effect of drought stress on seedlings. Nanotech fertilizer, tested in this study, showed positive results with seedlings in the nursery. Further studies should now proceed to test its application in seed bomb media.

5.6 Conclusions

The studied species were mostly orthodox and could be stored without losing of viability for at least twelve months, depending on species. Storage of recalcitrant species, even for short duration, was difficult and resulted in rapid viability reduction. Therefore, storage of recalcitrant species is unlikely to be successful without further development of more sophisticated methods.

Orthodox seeds could be sown either at collection time or stored and sown at the beginning of rainy season. In contrast, recalcitrant species must be sown immediately after collection, due to seeds' short viability. Differences in seedling yield and growth performance were not significantly different between seeds sown at collection time and after storage. Therefore, orthodox seeds can be sown at either time. However, the cost effectiveness of each sowing time should be considered, such as storage cost, drone usages etc.

Although previous studies have shown that hydrogel can improve soil condition, has high holding-water capacity and provides moisture to seeds and seedlings over long periods, my study showed that it did not support seed germination and reduce drought stress of native forest trees. Use of hydrogel on forest restoration is therefore not recommended.

The newly developed fertilizer (NANOTECH fertilizer) can be used for nursery propagation seedlings in lower amounts than conventional fertilizers. This fertilizer supported seedling growth, biomass and root-shoot ratio, but the cost of the fertilizer must be considered in designing cost effective seedling production or aerial seedling systems.

5.7 Recommendations

Automated forest restoration (AFR), using drones to drop seeds, should first be tested with large seeds, since they are mostly likely to be successful. However, development of AFR will depend on future research to devise the most appropriate deliver mechanism (seed bomb vs. pelleting) and their composition such as proportion of soil, inclusion of seed predator repellents, fertilizer, etc. in order to maximize seed germination, seedling yield and growth performance. In addition, seed bomb design is also an interesting area for further study. Seed bombs should remain stable when dropped on the ground and structure should support seed germination and early seedling establishment.

Seed predation may be a critical limiting factor. In this study, seed predation seriously impacted the hydrogel experiment. Preventing seed predation may be necessary for further study such as testing the effect of rodent repellents (both chemical and organic repellents) on seed germination and seedling growth.

The present study did not find any beneficial effects of using hydrogel but testing more species may be necessary to draw a definitive general conclusion on its use for AFR.

Recalcitrant species cannot be stored and must be sown very soon after seed collection. This would require separate flights for each species if implementing AFR, which might prove to be too expensive. On the other hand, recalcitrant species were in the minority in this study and further research might come up with ways to store them for the limited periods necessary to enable their use in AFR.

REFERENCES

Akhter, J., Mahmood, K., Malik, K. A., Mardan, A., Ahmad, M., & Iqbal, M. M. (2004). Effects of hydrogel amendment on water storage of sandy loam and loam soils and seedling growth of barley, wheat and chickpea. *Plant Soil and Environment*, 50(10), 463-469.

Al-Humaid, A. I., & Moftah, A. E. (2007). Effects of hydrophilic polymer on the survival of buttonwood seedlings grown under drought stress. *Journal of Plant Nutrition*, 30(1), 53-66.

AMAZON. (2017, March 30). Amazon prime air: Retrieved from https://www.amazon.com/Amazon-Prime-Air/b?node=8037720011.

Biocarbon Engineering. (2017, May 1). Overview of operation. Retrieved from http://www.biocarbonengineering.com/technologies.

Birkedal, M., Fischer, A., Karlsson, M., Löf, M., & Madsen, P. (2009). Rodent impact on establishment of direct-seeded *Fagus sylvatica*, *Quercus robur* and *Quercus petraea* on forest land. *Scandinavian Journal of Forest Research*, 24 (4), 298-307.

Bonn Challenge. (2017, March 30). A global effort. Retrieved from http://www.bonnchallenge.org/content/challenge.

Bunyavejchewin, S., Chamlongrach, Y., Buasalee, R., & Rayangkul, P. (2016). *Trees & Forest of Huai Kha Khaeng Wildlife Sanctuary*. Bangkok: Amarin Printing and Publishing.

Castro, J., Leverkus, A. B., & Fuster, F. (2015). A new device to foster oak forest restoration via seed sowing. *New Forests*, 46(5-6), 919-929.

CBD (Convention on Biological Diversity). (2017 a, March 30). Brazil biodiversity facts. Retrieved from https://www.cbd.int/countries/?country=br.

CBD. (2017 b, March 30). Thailand biodiversity facts. Retrieved from https://www.cbd.int/countries/?country=th.

Ceccon, E., González, E. J., & Martorell, C. (2016). Is direct seeding a biologically viable strategy for restoring forest ecosystems? evidences from a meta‐analysis. *Land Degradation & Development*, 27(3), 511-520.

Chirino, E., Vilagrosa, A., & Vallejo, V. R. (2011). Using hydrogel and clay to improve the water status of seedlings for dryland restoration. *Plant and soil*, 344(1-2), 99-110.

Da, L. J., & Guo, X. Y. (2014). Ecosystem restoration using the near-natural method in Shanghai. In *Sustainable Living with Environmental Risks* (pp. 203-221). Springer Japan.

Daws, M. I., Garwood, N. C., & Pritchard, H. W. (2006). Prediction of desiccation sensitivity in seeds of woody species: a probabilistic model based on two seed traits and 104 species. *Annals of Botany*, 97(4), 667-674.

De Jr, L., Hong, T. D., Arruda, Y. M. B. C., Mendes, A. M. S., & Ellis, R. H. (2014). Classification of seed storage behaviour of 67 Amazonian tree species. *Seed Science and Technology*, 42(3), 363-392.

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S Ramachandran, P.L. da Silva Dias, S.C. Wofsy and X. Zhang, (2007): Couplings Between Changes in the Climate System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

DNP (Department of National Park, Wildlife and Plant Conservation). (2017, March 30). Flora of Thailand. Retrieved from http://www.dnp.go.th/botany/Botany_Eng/FloraofThailand/ flora_Eng.html.

Doust, S. J., Peter, D., Erskine, P. D., & Lamb, D. (2006). Direct seeding to restore rainforest species: Microsite effects on the early establishment and growth of rainforest tree seedlings on degraded land in the wet tropics of Australia. *Forest Ecology and Management*, 234, 333-343.

Doust, S. J., Peter, D., Erskine, P. D., & Lamb, D. (2008). Restoring rainforest species by direct seeding: Tree seedling establishment and growth performance on degraded land in the wet tropics of Australia. *Forest Ecology and Management*, 256, 1178-1188.

Duangpatra, P. (2010). *Soil Conditioners*. Bangkok: Kasetsart University Press.

Dunford, R., Michel, K., Gagnage, M., Piégay, H., & Trémelo, M. L. (2009). Potential and constraints of Unmanned Aerial Vehicle technology for the characterization of Mediterranean riparian forest. *International Journal of Remote Sensing*, 30(19), 4915-4935.

Elliott, S. (2016). The potential for automating assisted natural regeneration of tropical forest ecosystems. *Biotropica*, 48(6), 825-833.

Elliott, S. (2017). Forest restoration concepts and the potential for its automation. Manuscript in preparation.

Elliott, S. D., Blakesley, D., & Hardwick, K. (2013). *Restoring tropical forests: A practical guide*. Richmond, Surrey, UK: Kew Publishing, Royal Botanic Gardens, Kew.

Elliott, S., Navakitbumrung, P., Kuarak, C., Zangkum, S., Anusarnsunthorn, V., & Blakesley, D. (2003). Selecting framework tree species for restoring seasonally dry tropical forests in northern Thailand based on field performance. *Forest Ecology and Management,* 184, 177-191.

Ellis, R. H., Mai-Hong, T., Hong, T. D., Tan, T. T., Xuan-Chuong, N. D., Hung, L. Q., ... & Le-Tam, V. T. (2007). Comparative analysis by protocol and key of seed storage behaviour of sixty Vietnamese tree species. *Seed Science and Technology*, 35(2), 460-476.

FAO (Food and Agriculture Organization of the United Nation). (2015). *Global guidelines for the restoration of degraded forests and landscapes in drylands: Building resilience and benefiting livelihoods*. Berrahmouni, N., Regato, P. & Parfondry, M (eds.). Rome, Food and Agriculture Organization of the United Nations.

FAO. (2016). *State of the World's Forests 2016. Forests and agriculture: Land-use challenges and opportunities*. Rome. Food and Agriculture Organization of the United Nations.

FAO. (2017, March 30). Sustainable Forest Management (SFM) Toolbox. Retrieved from http://www.fao.org/sustainable-forest-management/toolbox/en/.

Fields-Johnson, C. W., Zipper, C. E., Burger, J. A., & Evans, D. M. (2012). Forest restoration on steep slopes after coal surface mining in Appalachian USA: Soil grading and seeding effects. *Forest Ecology and Management*, 270, 126-134.

FORRU (Forest Restoration Research Unit). (2006). *How to plant a forest: The principles and practice of restoring tropical forests*. Department of Biology, Faculty of Science, Chiang Mai University, Chiang Mai, Thailand.

FORRU. (2008). *Research for restoring tropical forest ecosystems: A practical guide*. Department of Biology, Faculty of Science, Chiang Mai University, Chiang Mai, Thailand.

FORRU. (Unpublished data). FORRU database. Version 2016. Department of Biology, Faculty of Science, Chiang Mai University, Chiang Mai, Thailand.

Gardner, S., Sidisunthorn, P., & Anusarnsunthorn, V. (2000). *A field guide to forest trees of northern Thailand*. Bangkok. Kobfai Publishing Project.

Goosem, S. P., & Tucker, N. I. J. (1995). *Repairing the rain forest-theory and practice of rainforest re-establishment in North Queensland's wet tropics*. Wet tropics management authority, Cairns, 71 pp.

Green, V. S., & Stott, D. E. (1999, May). Polyacrylamide: A review of the use, effectiveness, and cost of a soil erosion control amendment. In *The 10th International Soil Conservation Organization Meeting* (pp. 384-389). Purdue University and the USDA-ARS National Soil Erosion Research Laboratory.

Guarino, E. D. S. G., & Scariot, A. (2014). Direct seeding of dry forest tree species in abandoned pastures: effects of grass canopy and seed burial on germination. *Ecological Research*, 29(3), 473-482.

Haase, D. L., Landis, T. D., & Dumroese, R. K. (2014). Outplanting. In *Tropical Nursery Manual A Guide to Starting and Operating a Nursery for Native and Traditional Plants*. Wilkinson, K. M., Landis, T. D., Haase, D. L., Daley, B. F., & Dumroese, R. K. (eds). United States Department of Agriculture.

Hardwick, K., Healey, J. R., Elliott, S., & Blakesley, D. (2004). Research needs for restoring seasonal tropical forests in Thailand: accelerated natural regeneration. *New Forests*, 27(3), 285-302.

Hau, C. H. (1997). Tree seed predation on degraded hillsides in Hong Kong. *Forest Ecology and Management*, 99(1), 215-221.

Hau C. H. (1999). The establishment and survival of native trees on degraded hillsides in Hong Kong. Ph.D thesis. The University of Hong Kong.

Hong, T. D., & Ellis, R. H. (1996). *A protocol to determine seed storage behaviour*. International Plant Genetic Resources Institute, Rome, Italy.

Houghton, R. A. (2012). Carbon emissions and the drivers of deforestation and forest degradation in the tropics. *Current Opinion in Environmental Sustainability*, 4(6), 597-603.

Hosonuma, N., Herold, M., De Sy, V., De Fries, R. S., Brockhaus, M., Verchot, L., ... & Romijn, E. (2012). An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*, *7*(4), 044009.

Hüttermann, A., Zommorodi, M., & Reise, K. (1999). Addition of hydrogels to soil for prolonging the survival of Pinus halepensis seedlings subjected to drought. *Soil and Tillage Research,* 50(3), 295-304.

IPCC (Intergovernmental Panel on Climate Change). (2013): *Climate Change 2013: The physical science basis. contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change.* Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

ISTA (International Seed Testing Association). (2006) *International rules for seed testing, rules.* International Seed Testing Association, Zurich, Switzerland.

Jacobs, F. D., & Landis, D. T. (2014). Plant Nutrition and Fertilization. In *Tropical Nursery Manual A Guide to Starting and Operating a Nursery for Native and Traditional Plants.* Wilkinson, K. M., Landis, T. D., Haase, D. L., Daley, B. F., & Dumroese, R. K. (eds). United States Department of Agriculture.

Jayasuriya, K. M. G. G., Wijetunga, S. T. B. A., Baskin, J. M., & Baskin C. C. (2013). Seed dormancy and storage behaviour in tropical Fabaceae: a study of 100 species from Sri Lanka. *Seed Science Research*, 23, 257-269.

Kuaraksa, C., & Elliott, S. (2013). The use of Asian *Ficus* species for restoring tropical forest ecosystems. *Restoration Ecology*, 21(1), 86-95.

Kopachon, S., Suriya, K., Hardwick, K., Pakaad, G., Maxwell, J., Anusarnsunthorn, V., Blakesley D, Garwood, N., & Elliott, S. (1996). Forest restoration research in northern Thailand: 1. The fruits, seeds and seedlings of Hovenia dulcis Thunb. (Rhamnaceae). *Nat Hist Bull Siam Soc,* 44,41–52.

Lal, R. (2005). Forest soils and carbon sequestration. *Forest Ecology and Management*, 220(1), 242-258.

Lamb, D., Erskine, P. D., & Parrotta, J. A. (2005). Restoration of degraded tropical forest landscapes. *Science*, 310 (5754), 1628-1632.

Landis, T. D., & Haase, D. L. (2012). Applications of hydrogels in the nursery and during outplanting. In: Haase, D.L., Pinto, J.R., & Riley, L.E. *National Proceedings: Forest and Conservation Nursery Associations*, Fort Collins (CO): USDA Forest Service.

Margono, B. A., Potapov, P. V., Turubanova, S., Stolle, F., & Hansen, M. C. (2014). Primary forest cover loss in Indonesia over 2000-2012. *Nature Climate Change*, *4*(8), 730-735.

McLaren, K. P., & McDonald, M. A. (2003). The effects of moisture and shade on seed germination and seedling survival in a tropical dry forest in Jamaica. *Forest Ecology and Management*, 183, 61-75.

Mikkelsen, R. L. (1994). Using hydrophilic polymers to control nutrient release. *Nutrient Cycling in Agroecosystems*, 38(1), 53-59.

Miyawaki, A. (1993). Restoration of native forests from Japan to Malaysia. In Leith, H. & Lohman, M. (eds). *Restoration of tropical forest ecosystems*. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp 5-24.

Miyawaki, A. (1998). Restoration of urban green environments based on the theories of vegetation ecology. *Ecological Engineering*, 11(1), 157-165.

Miyawaki, A. (2004). Restoration of living environment based on vegetation ecology: theory and practice. *Ecological Research*, 19(1), 83-90.

Naruangsri, K., & Tiansawat, P. (2016). Seed predation of five framework tree species in a degraded forest area of Chiang Mai, Thailand. In *Conservation Asia 2016 conference*, 29 June-2 July 2016, National University of Singapore, Singapore.

NESDB (National Economic and Social Development Board). (1992). Seventh National Economics and Social Development Plan B.E. 2535-2539. Retrieved from http://www.nesdb.go.th/ewt_w3c//ewt_dl_link.php?nid=3782.

ONREP (Office of Natural Resources and Environmental Policy and Planning). (2007). *Thailand Red Data: Vertebrates.* Ministry of Natural Resources and Environment. Bangkok. 98 pages.

Pakkad, G. (2005). *Developing seed storage protocols to optimize production of framework tree species for forest restoration* (Rep.). Biodiversity Research and Training Program (BRT).

Palma, A. C., & Laurance, S. G. (2015). A review of the use of direct seeding and seedling plantings in restoration: what do we know and where should we go?. *Applied Vegetation Science*, 18(4), 561-568.

Paneque-Gálvez, J., McCall, M. K., Napoletano, B. M., Wich, S. A., & Koh, L. P. (2014). Small drones for community-based forest monitoring: An assessment of their feasibility and potential in tropical areas. *Forests*, 5(6), 1481-1507.

Persson, M., Moberg, J., Ostwald, M., & Xu, J. (2013). The Chinese Grain for Green Programme: Assessing the carbon sequestered via land reform. *Journal of Environmental Management*, 126, 142-146.

Pinto, S. R., Melo, F., Tabarelli, M., Padovesi, A., Mesquita, C. A., de Mattos Scaramuzza, C. A., ... & César, R. G. (2014). Governing and delivering a biome-wide restoration initiative: the case of Atlantic Forest Restoration Pact in Brazil. *Forests*, 5(9), 2212-2229.

Pooma, R., & Suddee, S. (eds.). (2014). *Thai plant names Tem Smitinand revised edition 2014*. Bangkok: Office of the Forest Herbarium, Department of National Park, Wildlife and Plant Conservation.

Prentice, I. C., Farquhar, G. D., Fasham, M. J. R., Goulden, M. L., Heimann, M., Jaramillo, V. J., ... & Wallace, D. W. (2001). The carbon cycle and atmospheric carbon dioxide. Cambridge University Press.

RFD (Royal Forest Department). (2015). Forest statistic 1996-2015. Retrieved from http://forestinfo.forest.go.th/Content.aspx?id=9.

Ribeiro, M. C., Metzger, J. P., Martensen, A. C., Ponzoni, F. J., & Hirota, M. M. (2009). The Brazilian Atlantic Forest: How much is left, and how is the remaining forest distributed? Implications for conservation. *Biological conservation*, 142(6), 1141-1153.

Royal Botanic Gardens Kew. (2017). Seed information database (SID). Version 7.1. Retrieved from data.kew.org/sid/citing.html.

Sarvaš, M., Pavlenda, P., & Takáčová, E. (2007). Effect of hydrogel application on survival and growth of pine seedlings in reclamations. *J For Sci*, 53(5), 204-209.

Schirone, B., Salis, A., & Vessella, F. (2011). Effectiveness of the Miyawaki method in Mediterranean forest restoration programs. *Landscape and Ecological Engineering,* 7(1), 81-92.

Schmidt, L. (2007). *Tropical forest seed*. Springer-Verlag Berlin Heidelberg, 409 pp.

SER (Society for Ecological Restoration Science & Policy Working Group). (2002). The SER primer on ecological restoration. Retrieved from www.ser.org/.

Seub Foundation. (2016) *Thailand forest statistic 2015-2016*. Seub Foundation, Bangkok.

Shono, K., Cadaweng, E. A., & Durst, P. B. (2007). Application of assisted natural regeneration to restore degraded tropical forestlands. *Restoration Ecology*, 15(4), 620-626.

Stibig, H. J., Achard, F., Carboni, S., Rasi, R., & Miettinen, J. (2014). Change in tropical forest cover of Southeast Asia from 1990 to 2010. *Biogeosciences*, 11(2), 247.

Silva, R. R., Oliveira, D. R., da Rocha, G. P., & Vieira, D. L. (2015). Direct seeding of Brazilian savanna trees: effects of plant cover and fertilization on seedling establishment and growth. *Restoration Ecology*, 23(4), 393-401.

Sinhaseni, K. (2008). Natural establishment of tree seedlings in forest restoration trials at Ban Mae Sa Mai, Chiang Mai Province. M. Sc. Thesis, Chiang Mai University, Chiang Mai.

Sitthisuwannakul1, K., Boonpavanitchakul1, K., Muthitamongkol, P., & Kangwansupamonkon1, W. (2014). Polymer-layered silicate nanocomposite for slow released fertilizer. *The 4th Thailand international nanotechnology conference 2014.* 26-28 November 2014, Convention center, Thailand Science Park, Pathumthani, Thailand.

Song, X., Peng, C., Zhou, G., Jiang, H., & Wang, W. (2014). Chinese Grain for Green Program led to highly increased soil organic carbon levels: A meta-analysis. *Scientific Reports*, 4, srep04460.

Thapliyal, R. C., & Phartyal, S. S. (2005). Dispersal and germination syndromes of tree seeds in a monsoonal forest in northern India. *Seed Science Research*, 15(1), 29-42.

The Plant List. (2013). Version 1.1. Retrieved from http://www.theplantlist.org/.

Toktang, T. (2005). The effects of forest restoration on the species diversity and composition of a bird community in northern Thailand. M. Sc. Thesis, Chiang Mai University, Chiang Mai.

Tunjai, P. (2005). Appropriate tree species and techniques for direct seeding for forest restoration in Chiang Mai and Lamphun Provinces. M. Sc. Thesis, Chiang Mai University, Chiang Mai.

Tunjai, P., & Elliott, S. (2012). Effects of seed traits on the success of direct seeding for restoring southern Thailand's lowland evergreen forest ecosystem. *New Forests*, 43, 319-333.

Tweddle, J. C., Dickie, J. B., Baskin, C. C., & Baskin, J. M. (2003). Ecological aspects of seed desiccation sensitivity. *Journal of Ecology*, 91(2), 294-304.

Ullah, F., Othman, M. B. H., Javed, F., Ahmad, Z., & Akil, H. M. (2015). Classification, processing and application of hydrogels: A review. *Materials Science and Engineering*: C, 57, 414-433.

UN Climate summit. (2014). The New York declaration on forest action statements and action plans. Retrieved from http://www.un.org/climatechange/summit/wp-content/uploads/sites/2/2014/07/New-York-Declaration-on-Forest-–-Action-Statement-and-Action-Plan.pdf

Waiboonya, P.; Sumanochitrapon, W.; Larpkern, P.; Werukamkul, P.; and Ampornpan, L. (2014). *Plant Diversity in Dry Dipterocarp Forest Somdej Ya Learning Community Demonstration School, Bodhivijjala College, Srinakharinwirot University*. 2nd ed. Bangkok: Srinakharinwirot University.

Woods, K., & Elliott, S. (2004). Direct seeding for forest restoration on abandoned agricultural land in northern Thailand. *Journal of Tropical Forest Science*, 16(2), 248-259.

WWF (World Wildlife Fund). (2016). *Living Planet Report 2016. Risk and resilience in a new era*. WWF International, Gland, Switzerland.

Wydhayagarn, C., Elliott, S., & Wangpakapattanawong, P. (2009). Bird communities and seedling recruitment in restoring seasonally dry forest using the framework species method in northern Thailand. *New Forests*, 38, 81-97.

Zahawi, R. A., Dandois, J. P., Holl, K. D., Nadwodny, D., Reid, J. L., & Ellis, E. C. (2015). Using lightweight unmanned aerial vehicles to monitor tropical forest recovery. *Biological Conservation*, 186, 287-295.

Zhang, J., Hu, J., Lian, J., Fan, Z., Ouyang, X., & Ye, W. (2016). Seeing the forest from drones: Testing the potential of lightweight drones as a tool for long-term forest monitoring. *Biological Conservation*, 198, 60-69.

APPENDIX A

Study species

Plant descriptions in this study follow Bunyavejchewin et al. (2016), FORRU (2006), FORRU's database (unpublished data); Gardner et al. (2000) and Waiboonya et al. (2014). Plant Thai names follow Pooma, R., and Suddee, S. (2014). Plant scientific names and family names follow The Plant List (2013).

Acrocarpus fraxinifolius Arn., Leguminosae   สะเดาช้าง

Large tree up to 50 m, found at elevation 50-1,000 m above sea level, *Bark* pale grey with brown lenticels, inner bark pinkish. *Leaf* bipinnate with 4-9 pairs of leaflets. *Flower* from January to March, in dense spike-like clusters close to tip of leafless branches, 5 red petals with 5 bright green sepals. *Fruit* from April to June, pods black and shiny, flattened, dry splitting into 2 sections. 10-18 pale brown seed per pod, lens-shaped seeds (Figure 6.1), wind-dispersed.
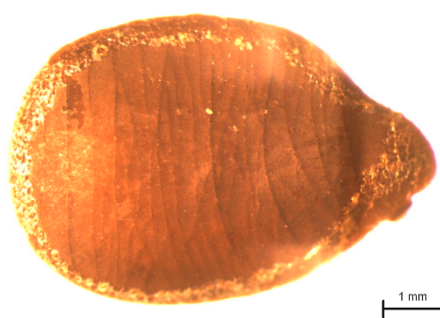

Figure 6.1 Seed of *Acrocarpus fraxinifolius.*

Adenanthera microsperma Teijsm. & Binn., Leguminosae   มะกล่ำตาไก่

Deciduous tree to 20 m, found at elevation 200-1,100 m above sea level. *Bark* dark brown or greyish, inner bark pale cream. *Leaf* bipinnate, doubly compound, 3-6 pairs, oval or oblong leaf. *Flower* from March to July, creamy-yellow turning orange with age. *Fruit* September to January, dried pod twisted in a tight coil, spitting to two strips. Seeds 5-8 mm, bright red (Figure 6.2), wind-dispersed.
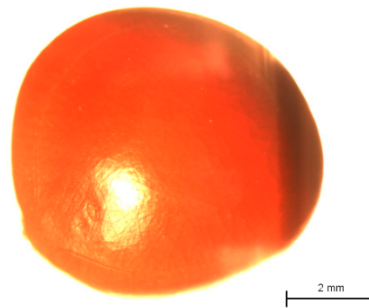
Figure 6.2 Seed of *Adenanthera microsperma.*

Alangium kurzii Craib, Cornaceae   สะลีกดง

Tree to 28 m found at elevation 600-1,400 m above sea level. *Leaf* ovate with heart-shaped base. Mature leaves densely covered with soft golden hair. *Flower* from March to May, 7-9 petals. *Fruit* from June to September, 1.2-1.5 cm, ripening dark purple to black, contains one black seed, oval with pointed ends (Figure 6.3).
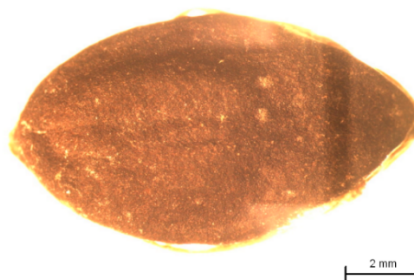
Figure 6.3 Seed of *Alangium kurzii.*

170

Artocarpus lacucha Buch.-Ham,   Moraceae   หาด

Deciduous tree to 24 m, found at elevation 200-1,500 m above sea level. *Bark* red brown to dark brown. *Leaf* oval to broadly ovate and rounded or slightly heart-shaped base. *Flower* from February to April, unisexual, yellow to pale pink or orange. *Fruit* from March to June, pale yellow or orange, irregularly globose, with oblong seeds (Figure 6.4) animal-dispersed.

Figure 6.4 Seed of *Artocarpus lacucha.*

Bauhinia variegata L., Leguminosae   เสี้ยวดอกขาว

Small deciduous tree to 15 m, found at elevation 350-1,500 m above sea level. *Bark* tan-brown to blackish. *Leaf* 2 lobes with rounded tips, young leaves pale green and mature leaves dark green. *Flower* from January to March, white or purple. *Fruit* from March-May pod splitting into 2 ribbons, 1 pod contains10-25 seeds, seed brownish and round (Figure 6.5).

Figure 6.5 Pod and seed of *Bauhinia variegata.*

Castanopsis tribuloides (Sm.) A.DC., Fagaceae   ก่อใบเลื่อม

Evergreen tree to 33 m, found at 550-2,350 m above sea level. *Bark* tan-brown to dark grey-brown. *Leaf* narrowly ovate blunt or slightly pointed base. *Flower* from April to June, unisexual. *Fruit* from July to October, oval shape, nut cover with spiny cupules, nut smooth, subglobose or ovoid (Figure 6.6), animal-dispersed.

Figure 6.6 Seed of *Castanopsis tribuloides.*

Choerospondias axillaris (Roxb.) B.L.Burtt & A.W.Hill, Anacardiaceae   มะมือ

Deciduous tree to 30 m, found at elevation 460-1,600 m above sea level. *Bark* dark grey, vertically cracked, inner bark red. *Leaf* once pinnate, narrowly ovate or lanceolate, young leaves with scattered teeth and mature leaves often without teeth. *Flower* from February to May, unisexual, dark red, 5 petals. *Fruit* from May to August, green or yellow, single pyrene with 5 locules (Figure 6.7), animal-dispersed.

Figure 6.7 Pyrenes of *Choerospondias axillaris.*

Dimocarpus longan Lour., Sapindaceae　　　　　　　　　　　　　　ลำไยป่า

Evergreen tree to 30 m, found at Elevation 60-1,400 m above sea level. *Bark* grey to red-brown, smooth or slightly flaking, inner bark pinkish. *Leaf* once pinnate, dark green above, paler below, dark glands in vein axils. *Flower* from March to May, unisexual, white or cream, 5 petals. *Fruit* from June to September, brown or yellowish, globular, not splitting, single large glossy dark brown (Figure 6.8), seed with fleshy covering, animal-dispersed.
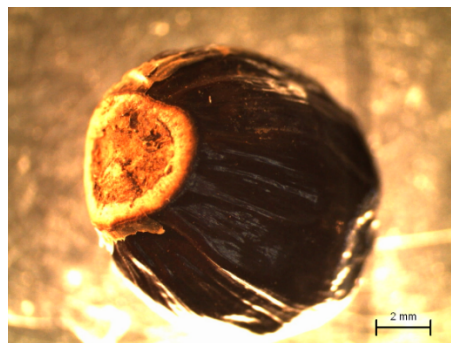
Figure 6.8 Seed of *Dimocarpus longan.*

Diospyros glandulosa Lace, Ebenaceae　　　　　　　　　　　　　　กล้วยฤๅษี

Partly deciduous tree to 15 m, found at Elevation 650-1,650 m above sea level. *Bark* grey to brown, inner bark yellow. *Leaf* narrowly elliptic-oblong. *Flower* from March to May, unisexual, 4(5) pink petals and 4(5) sepals. *Fruit* from May to October, yellow-orange, globose or oval, 3-7 dark brown seeds (Figure 6.9), animal-dispersed.

Figure 6.9 Seed of *Diospyros glandulosa.*

173

Gmelina arborea Roxb., Lamiaceae ซ้อ

Deciduous tree 20-30 m, found at elevation 200-1,475 m above sea level. *Bark* pale creamy-brown or greyish, smooth with pale corky lenticels. Leaf oval or broadly ovate flattened or slightly heart-shaped base. *Flower* from February to March, yellow-brown. *Fruit* from March to May, greenish-yellow, smooth and slightly glossy, globose or obovoid fleshy with a 1-2 seed(s) (Figure 6.10), animal-dispersed.

Figure 6.10 Seed of *Gmelina arborea.*

Horsfieldia glabra (Reinw. ex Blume) Warb., Myristicaceae เลือดม้า

Evergreen small to medium tree to 10-25 m, found at elevation 200-650 m above sea level. *Bark* grey-brown, hard and brittle, inner bark yellow. *Leaf* smooth, dark green. *Flower* from September to October, unisexual, pale yellow. *Fruit* from January to May, yellow, smooth, oblong seed, covered with orange coating (Figure 6.11), animal-dispersed.

Figure 6.11 Fruit and Seed of *Horsfieldia glabra.*

Hovenia dulcis Thunb., Rhamnaceae   หมอนหิน

Deciduous tree to 20 m, found at 1,205-1300 m above sea level. *Bark* brown or black-purple. *Leaf* blade ovate, broadly oblong. *Flower* from May to July, yellow-green. *Fruit* from August to October, black nut contains 3 seeds, seeds dark brown, 5-5.5 mm in diameter (Figure 6.12).

Figure 6.12 Nut and seed of *Hovenia dulcis.*

Magnolia garrettii (Craib) V.S.Kumar, Magnoliaceae   มณฑาป่า

Partly deciduous tree to 25 m, found at elevation 1,050-1,600 m above sea level. *Bark* greyish. *Leaf* dark green above, greyish-green below, smooth. *Flower* from March to April, dark pink-purple. *Fruit* from September to November ovoid, seed cover by thin red coating, ovate shape with pointed end (Figure 6.13).
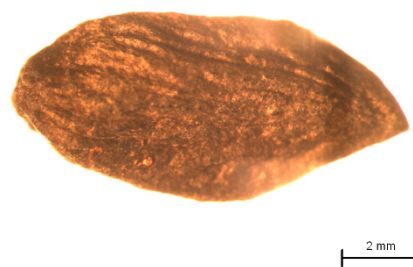

Figure 6.13 Seed of *Magnolia garrettii.*

Melia azedarach L., Meliaceae   เลี่ยน

Deciduous tree to 25 m, found at elevation 500-1,450 m above sea level. *Bark* pale grey or brown, inner bark cream. *Leaf* bipinnate or tripinnate, mature leaflets smooth. *Flower* from January to March, white with violet centre, 5-6 small triangular sepals, 5-6 white petals. *Fruit* from August to March green, ripening yellowish, single stone contain six black shiny seeds (Figure 6.14).

Figure 6.14 Seed of *Melia azedarach.*

Phyllanthus emblica L., Phyllanthaceae   มะขามป้อม

Small to medium deciduous tree to 8-20 m, found at elevation 10-1,500 m above sea level. *Bark* grey-brown with creamy orange patches, smooth, inner bark pink. *Leave*, oblong or linear with blunt tip, usually asymmetric. *Flower* from January to February, unisexual, pale green or creamy-yellow. *Fruit* from October to March, green, ripening yellowish, globose, with a hard stone contains section with 1-2 seeds, seeds dark brown (Figure 6.15), animal-dispersed.
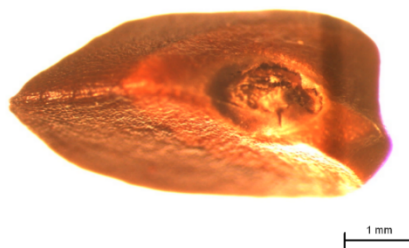

Figure 6.15 Seed of *Phyllanthus emblica.*

Prunus cerasoides Buch.-Ham. ex D.Don, Rosaceae   ชมพูภูภิงค์

Small to medium deciduous tree, found at elevation 1,050-1,750 m above sea level. *Bark* red-brown with large lenticels. *Leaf* narrowly ovate, sharply toothed. *Flower* from December to February, bright pink or rarely white. *Fruit* from February to May, pink or bright red with single stone (pyrene, Figure 6.16), animal-dispersed.
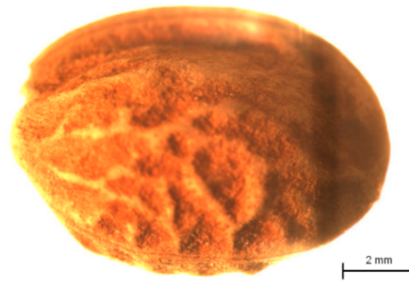

Figure 6.16 Pyrene of *Prunus cerasoides.*

Spondias pinnata (L. f.) Kurz, Anacardiaceae   มะกอก

Deciduous tree to 20-30 m, found at elevation 50-900 m above sea level. *Bark* pale grey, smooth, inner bark pink. *Leaf* once pinnate, alternate, elliptic or oblong, often slightly asymmetric. *Flower* from January to March, white or creamy yellow, 5(4) petals. *Fruit* from September to March, green, ripening yellowish with scatter brown spots, a single large stone consisting up to 5 seeds (Figure 6.17), animal-dispersed.

Figure 6.17 Fruits and seed of *Spondias pinnata.*

Syzygium albiflorum (Duthie ex Kurz) Bahadur & R.C.Gaur Myrtaceae   มะห้า

Evergreen tree to 20 m. *Bark* red-brown or pale grey. *Leaf* narrowly ovate or lanceolate. *Flower* from February to April, white or cream. *Fruit* from June to August, pale green to dark purple-black, globose (Figure 6.18).

Figure 6.18 Seeds of *Syzygium albiflorum*.

CURRICULUM VITAE

Author's Name	Mr. Panya Waiboonya
Date/Year of Birth	18 July 1985
Place of Birth	Bangkok

Education

2010: M. Sc. in Applied Ecology: European programme, University of East Anglia, Norwich, UK.

2010: European Master in Applied Ecology, Université de Poitiers, Poitiers, France

2010: European Master in Applied Ecology, Universidade de Coimbra, Coimbra, Portugal.

2008: Graduate Diploma in Teaching Profession, Srinakharinwirot University, Bangkok, Thailand.

2007: B. Sc. in Biology, First Class Honours. Srinakharinwirot University, Bangkok, Thailand.

Scholarship

2008-2010: Erasmus Mundus Scholarship in programme entitle "European Master in Applied Ecology" From education, Audio visual and culture Executive Agency, European Commission.

2007: (September) Internship from the Belgian Focal Point to the Global Taxonomy Initiative (GTI) for training in insect taxonomy and collection management at the Royal Belgian Institute of Natural Sciences, Brussels, Belgium.

<table>
<tr><td></td><td>2003-2007: Scholarship from the Project for the Promotion of Science and Mathematics Talented Teachers (PSMT) (4 years in science degree and 1 year in education degree).</td></tr>
<tr><td>Publications</td><td>Larpkern, **P.; Waiboonya**, P.; Moungsrimuangdee, B.; and Yodsanga, P. (2013). *Forest and Community: Case Study of Ban Mae Keed Luang Community Forest, Mae Sod district, Tak province.* Bangkok: Bodhivijjala College, Srinakharinwirot University.</td></tr>
</table>

Larpkern, P., Eriksen, M. & **Waiboonya, P**. (2017). Diversity and Uses of Tree Species in the Deciduous Dipterocarp Forest, Mae Chaem District, Chiang Mai Province, Northern Thailand. Naresuan University Journal: Science and Technology, 25 (3).

Larpkern, P., **Waiboonya P**., Moungsrimuangdee, B & Kosuwan, S. (2016). Selecting Native Tree Species For Restoring Disturbed Mixed Deciduous Forest At Ban Mae Kued Luang Community Forest, Mae Sot District, Tak Province. *SWU Sci. J.* 32 (2): 137-149.

Moungsrimuangdee, B., **Waiboonya, P**., Larpkern, P., Yodsanga, P., Saeyang, M. (2017). Reproductive Phenology and Growth of Riparian Species along Phra Prong River, Sa Kaeo Province, Eastern Thailand. *Journal of Landscape Ecology*. 10 (2): 5-18.

Waiboonya, P.; Sumanochitrapon, W.; Larpkern, P.; Werukamkul, P.; and Ampornpan, L. (2014). *Plant Diversity in Dry Dipterocarp Forest Somdej Ya Learning Community Demonstration School, Bodhivijjala College, Srinakharinwirot University*. 2nd ed. Bangkok: Srinakharinwirot University.

Experiences	2013 (January-September) Assistant dean for planning and administrative affairs.
	2012-present: Lecturer at college of Bodhivijalaya, Srinakharinwirot University.
	2008-2011: Lecturer at programme of agriculture, Faculty of Agriculture and Life Sciences, Chandrakasem Rajabhat University.