Direct Seeding for Restoring Tropical Lowland Forest Ecosystems in Southern Thailand

Panitnard Tunjai

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy Program in
Ecology and Biodiversity
Walailak University

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ชื่อวิทยานิพนธ์ วิธีหยอดเมล็ดสำหรับการฟื้นฟูระบบนิเวศป่าที่ราบต่ำเขตร้อนในภาคใต้ของประเทศไทย
ผู้เขียน พนิตนาถ ทันใจ
สาขาวิชา นิเวศวิทยาและความหลากหลายทางชีวภาพ
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บทคัดย่อ

การตัดไม้ทำลายป่าเป็นสาเหตุหลักของการสูญเสียความหลากหลายทางชีวภาพระดับโลกที่ส่งผลต่อการสูญเสียผลผลิตจากป่าและการบริการจากระบบนิเวศ นอกจากนี้ยังเป็นต้นเหตุของการปล่อยคาร์บอนสู่ชั้นบรรยากาศที่เกิดจากมนุษย์คิดเป็นร้อยละ 20-25 การขยายตัวของพื้นที่เกษตรกรรมเชิงเดี่ยวและความเป็นเมืองส่งผลต่อการลดลงของความหลากหลายทางชีวภาพในภาคใต้ของประเทศไทย โดยเฉพาะอย่างยิ่งการสูญเสียป่าที่ราบต่ำเขตร้อนซึ่งกระจายตัวเป็นบริเวณกว้างในอดีตแต่ถูกแบ่งเป็นพื้นที่ขนาดเล็กเป็นหย่อมๆ ในปัจจุบัน การปลูกต้นไม้เป็นวิธีฟื้นฟูป่าที่มีค่าใช้จ่ายสูงแต่ใช้กันอย่างแพร่หลายเนื่องจากไม่มีทางเลือกมากนัก ดังนั้นวิธีฟื้นฟูป่าที่มีค่าใช้จ่ายต่ำและสามารถประยุกต์ใช้กับพื้นที่ขนาดใหญ่จำเป็นต้องได้รับการพัฒนาเพื่อรับมือกับผลลัพธ์จากการตัดไม้ทำลายป่าในเขตร้อน

วิธีหยอดเมล็ดเป็นทางเลือกหนึ่งสำหรับเร่งการฟื้นตัวของป่าในพื้นที่เสื่อมโทรมด้วยค่าใช้จ่ายต่ำที่สุด อย่างไรก็ตามความสำเร็จของวิธีนี้ถูกลดทอนด้วยอัตราการงอกของเมล็ดที่ต่ำ ความเสี่ยงต่อการสูญเสียเมล็ด อัตรารอดตายและการเจริญเติบโตของกล้าไม้ที่ไม่ค่อยดีนัก การศึกษานี้มีวัตถุประสงค์เพื่อค้นหาชนิดพันธุ์ วิธีการที่มีประสิทธิภาพและเหมาะสมสำหรับการหยอดเมล็ดเพื่อฟื้นฟูป่าที่ราบต่ำเขตร้อนในภาคใต้ของประเทศไทย เพื่อสามารถระบุปัจจัยแวดล้อมและลักษณะของชนิดพันธุ์ซึ่งมีส่วนต่อความสำเร็จและอาจพัฒนาให้เหมาะสมกับระบบนิเวศอื่นต่อไป

มีการบันทึกข้อมูลชีพลักษณ์ของพรรณไม้ 43 และ 35 ชนิด ในหย่อมป่าบนพื้นที่ชายฝั่งด้านตะวันตกและตะวันออกของภาคใต้เป็นเวลา 1 ปี พบว่าพรรณไม้ 12 และ 15 ชนิด มีผลสุกในช่วงต้นฤดูฝนซึ่งเหมาะสำหรับการฟื้นฟูป่าโดยวิธีหยอดเมล็ดของพื้นที่ชายฝั่งด้านตะวันตกและตะวันออกตามลำดับ จากการศึกษาลักษณะของเมล็ดพบว่า ขนาด รูปทรง และความชื้นเมล็ดสามารถใช้เป็นเกณฑ์ในการคัดเลือกชนิดพันธุ์ที่มีศักยภาพสำหรับวิธีหยอดเมล็ด ชนิดพันธุ์ที่มี

ความชื้นระดับต่ำถึงปานกลาง ขนาดปานกลางถึงใหญ่ และรูปร่างเมล็ดรีถึงกลม มีโอกาสเป็นชนิดพันธุ์ที่เหมาะสมด้วยระดับความเชื่อมั่นประมาณร้อยละ 70

จากผลการศึกษาพบว่าพืชวงศ์ถั่ว (Leguminosae) และวงศ์มะเดื่อ (Moraceae) เป็นนักบุกเบิกที่ประสบความสำเร็จและมีอัตราการเจริญเติบโตที่ดีมากแม้ในพื้นที่เสื่อมโทรม รองลงมาคือสมาชิกวงศ์มะพลับ (Ebenaceae) วงศ์ตะขบฝรั่ง (Tiliaceae) และวงศ์สัก (Verbenaceae) นอกจากนี้ ชนิดพันธุ์ที่ผลิตผลสดและส่วนมากกระจายเมล็ดโดยสัตว์นับว่าเป็นเป้าหมายที่มีศักยภาพสำหรับการหยอดเมล็ดช่วงต้นฤดูฝน การศึกษาครั้งนี้เน้นให้เห็นถึงความสำคัญของการคัดเลือกชนิดพันธุ์ที่มีอย่างจำกัดในช่วงต้นฤดูฝนซึ่งส่งผลอย่างมากต่อความสำเร็จของการฟื้นฟูป่าโดยวิธีหยอดเมล็ด

การศึกษานี้มีการเก็บเมล็ดพรรณไม้ 30 ชนิด (20 ชนิด ในพื้นที่ชายฝั่งด้านตะวันตก 14 ชนิด ชายฝั่งด้านตะวันออก ทั้งนี้มี 4 ชนิด ที่พบทั้งสองบริเวณ) เพื่อเปรียบเทียบระหว่างวิธีหยอดเมล็ดกับการปลูกต้นไม้ที่ใช้กล้าไม้จากการเพาะเมล็ด ทั้งนี้เมล็ดจะถูกเพาะที่เรือนเพาะชำและแปลงทดลองในช่วงเวลาเดียวกัน มีการเก็บข้อมูลการงอก การตั้งตัวของกล้าไม้และการเจริญเติบโต ที่อาจได้รับผลกระทบจากการคลุมเมล็ด การเพิ่มธาตุอาหารในดิน และการป้องกันเมล็ดจากการถูกทำลาย จากผลการศึกษาพบว่าปัจจัยทั้งหมดไม่มีผลต่อการตั้งตัวของกล้าไม้และการเจริญเติบโตอย่างมีนัยสำคัญในช่วงปีแรกหลังการหยอดเมล็ด แสดงว่าความชื้นและธาตุอาหารที่ต่ำมากในดิน รวมไปถึงการถูกล่าเมล็ดไม่ใช่ปัจจัยจำกัดสำหรับการตั้งตัวและการเจริญเติบโตในระยะแรกของกล้าไม้ที่เจริญมาจากการหยอดเมล็ดในแปลงทดลอง หลังการหยอดเมล็ด 1 ปี กล้าไม้ที่ผลิตจากเรือนเพาะชำจำนวน 26 ชนิด ถูกนำไปปลูกในแปลงทดลองที่ระยะห่างระหว่างต้นประมาณ 50 เซนติเมตร จากกล้าไม้ที่ตั้งตัวได้จากวิธีหยอดเมล็ด จำนวน 25 ชนิด เพื่อเปรียบเทียบการเจริญเติบโตและค่าใช้จ่ายทั้งหมด หลังจากการหยอดเมล็ด 18 เดือน พบว่ากล้าไม้ในแปลงทดลองมีการเจริญเติบโตที่ดีมาก ค่าเฉลี่ยของทุกตัวแปรสูงกว่ากล้าไม้ที่ผลิตจากเรือนเพาะชำประมาณ 2 เท่า วิธีหยอดเมล็ดสามารถประหยัดค่าใช้จ่ายได้ประมาณร้อยละ 30 โดยมีความหนาแน่นของกล้าไม้ที่ตั้งตัวได้ไม่แตกต่างกัน คิดเป็นต้นทุน 33 และ 45 บาทต่อต้น สำหรับวิธีหยอดเมล็ดและการปลูกจากกล้าไม้ ตามลำดับ

การศึกษาครั้งนี้แสดงให้เห็นศักยภาพของวิธีหยอดเมล็ดเพื่อการฟื้นฟูป่าที่ราบต่ำเขตร้อนในบริเวณกว้าง โดยเฉพาะอย่างยิ่งค่าใช้จ่ายที่ต่ำกว่ามากเมื่อเปรียบเทียบกับการฟื้นฟูป่าโดยการปลูกกล้าไม้ อย่างไรก็ตามเพื่อที่จะให้สามารถนำวิธีการนี้ไปใช้ประโยชน์ได้อย่างแท้จริง ควรมีการศึกษาชนิดพันธุ์ที่หลากหลายและสัดส่วนของชนิดที่เหมาะสมในการหยอดเมล็ดแต่ละครั้ง

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Abstract

Deforestation is a major cause of loss of biodiversity globally, resulting in losses of forest products and ecological services. It also accounts for 20-25% of anthropogenic carbon emissions into the atmosphere. Expansion of monoculture plantations and urbanization has resulted in biodiversity depletion in southern Thailand, particularly due to loss of lowland tropical forest that was formerly widespread, but has become sparse and fragmented. Planting trees is the most intensive and expensive of forest restoration techniques but has been conducted worldwide, due to lack of alternatives. Low cost restoration techniques that can be applied on a large scale must therefore be developed to begin to reverse the effects of tropical deforestation.

Direct seeding has been suggested as a way to accelerate forest regeneration on degraded areas at minimal cost. However, the success of this technique is hindered by low germination rates, susceptibility of seeds to predation, and poor survival and growth of established seedlings. This study investigated which tree species and which technique are most effective and suitable for restoring lowland tropical forest in S. Thailand direct seeding. It also identified the general factors and tree species characteristics that contribute to success, so that direct seeding techniques may be more easily developed for other forest ecosystem types.

Forty-three tree species were monitored in their natural forest habitats, for one year on the west coast and 35 tree species on the east coast of southern Thailand. Twelve and 15 species, respectively, bore ripe fruits prior to the rainy season and should be targeted for seed collection for direct seeding. Analysis of seed characteristics revealed that seed size, shape and moisture content can be used as guidelines for selecting potential 1candidate for direct seeding. Species having oval to round, large or intermediate-sized seeds and with low or medium moisture contents are more likely to be suitable for direct seeding at about 70% confidence.

Tree species of the families Leguminosae and Moraceae were the most successful colonizers of degraded areas as a result of direct seeding, showing excellent growth performance. Other families with high performance included Ebenaceae, Tiliaceae and Verbenaceae. Moreover, species with fleshly fruits and mostly dispersed by animals could be identified of particularly suitable candidates for seed sowing in the early rainy season. These studies show that seed availability and species selection are the important factors linked to the success of direct seeding.

Direct seeding was compared with conventional tree planting, using nursery-raised planting stock from seed. Thirty species were studied (20 on the west coast and 14 on the east coast, with 4 species overlapping between both sites). Seeds were sown in the nursery and the field at the same time. The effects of mulching, soil nutrient supply and seed predator exclusion on the germination, establishment and growth performance of direct-seeded species were investigated. None of these treatments resulted in significantly higher seedling establishment and growth over the first year after sowing, suggesting that low soil moisture and nutrient, and seed predation are not limiting factors for early establishment and growth of direct-seeded plants, in the study sites. One year after sowing, 26 tree species nursery-grown plants were transplanted into the field, randomly next to the 25 surviving species of direct-seeded tree seedlings, 50 cm apart, and growth performance and costs were compared. Excellent growth performance of direct seeded plants was demonstrated with means of all measured growth parameters being twice as large as compared to nursery-raised plants at 18 months after early sowing. Direct seeding could save about 30% with less cost per tree (33 and 45 baht per tree for direct-seeded and nursery-grown seedlings respectively) with comparable density of successfully recruit seedlings (about 2700 seedlings ha^{-1}).

This study shows that direct seeding has great potential for the restoration of tropical lowland forests, on a large scale, at much lower costs than conventional reforestation by tree planting. However, in order to realize these benefits a broader range of tree species should be tested and optimal species composition determined.

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I am greatly indebted to my supervisor Dr. Stephen Elliott for his invaluable advice, assistance and patience throughout this study. His enthusiasm for improving our understanding of forest restoration in Thailand set a good model for my study and work. I also extremely grateful to Assistant Professor Dr. Pitiwong Tantichodok, who has given me much inspiration on ecology and initiated the Ecology and Biodiversity Program at Walailak University. I greatly appreciate and thank Dr. Shawn K. Y. Lum, who has given me challenging ideas and always encourage me with cheerful suggestions.

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Panitnard Tunjai

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List of Abbreviations

GF = General flowering or mass flowering
KB = Krabi Province
MLD = Median length of dormancy
MRGR = Mean of relative growth rate
NST = Nakhon Si Thammarat Province
RCD = Root collar diameter

Chapter 1

Introduction

1.1 Tropical deforestation

Tropical forests are among the biologically richest ecosystems on Earth, but are being rapidly degraded and destroyed by habitat conversion (De Lacerda & Nimmo, 2010; Laurance et al., 2011). The actual rate of deforestation is difficult to determine, however there is the TREES project that dedicated to the development of techniques for global tropical forest cover assessment and for monitoring deforestation using satellite imagery (Achard et al., 2002). The study of Achard et al. (2002) pointed out that the tropical forests are disappearing at an estimated rate of 58,000 km^2 yr^{-1} (0.52%), there were the considerable differences in percentage change rate among regions, and the highest was in Southeast Asia (25,000 km^2 yr^{-1}, 0.91%). Deforestation is typically assessed by quantifying the amount of area deforested, measured at the present time, however from environment point of view, De Barros Ferraz et al. (2009) emphasized that quantifying the damage and its possible consequences is a more important task, and a broader perspective of the deforestation process that includes consideration of historical patterns is needed for restoration planning.

Deforestation occurs in many ways, most of the clearing happens principally through agricultural expansion, uncontrolled livestock ranging, logging, forest-colonization schemes and forest fire (Briant et al., 2010; Gaveau et al., 2009; Martinez-Garza et al., 2005; Parrotta et al., 1997). The causes of deforestation are very complex; they could be a competitive global economy, corruption, weak of law enforcement, poor, lacking of knowledge or greedy (Gaveau et al., 2009; Lindenmayer, 2010; Urquhart et al., 1998).

Deforestation is a major causes of loss of biodiversity globally (Ford et al., 2009). We do not know the exact rate of extinction, but estimates indicate that up to 137 species disappear worldwide each day (Urquhart et al., 1998). Not only biodiversity loss, we lost invaluable services when the tropical forest disappeared since these forests provide many regulating services that operate at different spatial scales (Guariguata & Balvanera, 2009). For example, they are global players in the atmospheric carbon cycle (Clark, 2007), modulate regional rainfall regimes (Salati & Vose, 1984), and provide refugia for pollinators of agricultural crops in small-holder farms (Ricketts, 2004). It is also in the tropics where millions of people rely on forest ecosystem services to sustain traditional and contemporary livelihoods (Bawa et al., 2004).

The amount of carbon held in trees is 20-50 times higher in forests than in cleared lands, and changes in carbon stocks vary with the type of land use, with the type of ecosystem, and with the tropical region (Houghton, 2005). Houghton (2003) calculated the net release of carbon from tropical deforestation and reforestation to have been nearly 100 PgC between 1850 and 2000. Over this period, the total net flux of carbon from changes in land use is approximately half of the amount of carbon emitted from combustion of fossil fuels. It is estimated that under current emissions trends, by 2100 average temperature will increase between 4° and 7° C, with potentially catastrophic social and environmental consequences, including rising sea levels, inundation of coastal cities, and large-scale ecosystem transformations (Moutinho et al., 2005).

1.2 Rehabilitation and restoration of degraded forest

Research on forest rehabilitation has often focused on the role of tree plantations in accelerating secondary succession in altered areas (Parrota, 1992; Lugo, 1997) while the most ambitious goal of restoration is to attempt to reestablish the original forest ecosystem (Lamb et al., 2005). The Society for Ecological Restoration defines it as "the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed". However, it is even more difficult to measure forest degradation than it is to measure deforestation. One method involves assessing the area of former lands that are now grassland or shrubland and which might be available for reforestation (Lamb & Gilmour, 2003).

The degradation of forest resources is a global issue and represents a considerable threat to both the functioning of ecosystems and the well-being of human communities (Orsi & Geneletti, 2010). A number of factors impede tropical forest recovery in degraded area has been indicated, the most important barriers are lack of dispersal of forest seeds and seedling competition with grasses (Holl et al., 2000). There have been various responses to these losses in forest cover and quality. More commonly, reforestation has been carried out using large- or small-scale plantation monoculture. Most of these plantations consist of exotic species and most involve very few tree species. For example, a limited number of species from just four genera (*Acacia*, *Eucalyptus*, *Pinus* and *Tectona*) account for the majority of tropical plantations (Lamb & Gilmour, 2003). Although many of these plantations have been productive and generated goods such as pulpwood, few provide the variety of goods (e.g. timbers, medicines, and foods) once provided by the original forests to the people living in these areas (Lamb et al., 2005). In addition, their simple composition and structure rarely contribute significantly to biodiversity conservation (Lamb & Gilmour, 2003) and a steady flow of ecosystem services (Guariguata & Balvanera, 2009).

In recent year, new forms of reforestation have been tested that may offer additional ways of dealing with degraded tropical forest landscapes. Two broad approaches have been tested; one approach is to use a small number of fast-growing but short-lived tree species to create canopy cover, and the success depends on the ability of additional native species to reach the site from nearby intact forest (Lamb et al., 2005). This approach was reported repeatedly to be the most successful strategy, since it could simultaneously enhance seed dispersal, improve soil and microclimatic conditions, and shade out aggressive herbaceous vegetation (Holl & Kappelle, 1999; Martinez- Garza et al., 2005). The other approach uses a much greater number of species representative of more mature successional stages and bypasses the natural successional sequence (Lamb et al., 2005). This approach requires sufficient ecological knowledge to be able to collect seeds and germinate large numbers of seedlings from a wide variety of species (FORRU, 2008a), and the key limitation is its high cost (Erskine, 2002).

Degradation needs to be addressed in a variety of ways and at a range of scale. While site-level interventions are important, they need to be coordinated with effective planning at the landscape level (Lamb & Gilmour, 2003). In 2000, the International Union for Conservation of Nature (IUCN) and the World Wildlife Fund (WWF) proposed the Forest Landscape Restoration (FLR) approach as an innovative one that aims at regaining ecological integrity while enhancing human well-being (Orsi & Geneletti, 2010). The main goal is not enhancing wood cover or bringing the ecosystem back to a pristine state, but rather to build up a forest-based landscape that is good for both nature and people (Maginnis & Jackson, 2002).

1.3 Restoration techniques

Restoration has, in some way, been practiced for centuries but only recently has it started to receive society's attention and the scientific support of a young discipline, restoration ecology (Cairns & Heckman, 1996; Palmer et al., 2006; Young et al., 2005). Restoration practice has greatly evolved from non-scientific, trial-and-error, forest plantations to projects based on many ecological concepts and theories that are now being put to the test (Young et al., 2005). These restoration efforts range from removing human disturbances (e.g. fire, grazing, water removal from rivers) in order to allow for natural or unassisted recovery (passive restoration) to humans actively intervening in an effort to accelerate and influence the successional trajectory of recovery (active restoration) (Holl & Aide, 2010).

Passive restoration is achieved by simply protecting the site from further disturbances and allowing natural colonisation and successional processes to restore ecosystem biodiversity and structure. Passive restoration is especially advantageous when there are limited financial resources available and it may be one of the few approaches that can be attempted across large areas (Aide et al., 2000; Lamb & Gilmour, 2003).

Enrichment planting (also known as strip-, gap- and under-planting) is defined as the introduction of valuable species to degraded forests without the elimination of valuable individuals already present. It has been suggested as a technique for restoration of overexploited and secondary forests as it can increase total tree volume and the economic value of forests (Montagnini et al., 1997). Moreover, enrichment planting may be useful to supplement biological diversity by reintroducing certain key species to hasten the process of natural recovery. Or these might be endangered plant species, plant with large seeds that are poorly dispersed or plants needed by a particular wildlife species (Lamb & Gilmour, 2003).

Another way to accelerate succession is to foster the structural complexity that attracts seed- or fruit-dispersing fauna into the degraded landscape from nearby intact forest. One method called 'scattered tree planting' involves planting small numbers of scattered, single trees or clumps or rows of trees, which form perches for birds (Lamb & Gilmour, 2003). Similarly, Janzen (1988) described an approach in a situation where most tree species were dispersed by wind rather than wildlife. In that case wind-dispersed species were planted across the landscape in rows perpendicular to the prevailing wind and the rows were spaced at a distance equivalent to the average dispersal distance of the seed. Wind dispersal ensured subsequent blanket coverage of the site by tree seeds. The approach is probably most useful in abandoned farmlands with grasslands or shrubs and at sites without many trees (Lamb & Gilmour, 2003).

In addition, 'Close-spaced planting using limited numbers of species' has been referred to as the framework species method (Goosem & Tucker, 1995). This technique is to use more closely spaced plantings of a small number of species able to attracted seed-dispersed birds. Target species might come from early successional stages or species might be chosen because they are tolerant of the site conditions or because they are attractive to wildlife, and are able to reproduce quickly and spread across the site (Lamb & Gilmour, 2003). The approach is especially suited to areas close to intact forest that can act as a source of seeds and wildlife; this allows additional species to be recruited quickly (FORRU, 2006b).

To plant a large number of tree and understory species has been known as 'intensive ecological reconstruction using dense planting of many species' (Lamb & Gilmour, 2003) or the Miyawaki method by Miyawaki (1993) or the maximum diversity method by Goosem and Tucker (1995) – uses more intimate mixtures and denser plantings and attempts to restore as much as possible of the site's original botanical and structural diversity. A range of life forms and successional stages should be included in dense plantings of up to 4,000 plants per ha. This approach may useful in areas where natural recolonisation is slow because of isolation from intact forest remnants, since it could quickly establish a large number of species (Lamb & Gilmour, 2003).

All the approaches described involve planting seedlings or preventing further disturbances. Another way to accelerate succession is to deliberately reintroduce the seed or 'direct seeding' on degraded areas. The advantages of direct seeding are its low cost (Cole et al., 2011; Doust et al., 2006; Engel & Parrotta, 2001; Lamb & Gilmour, 2003) and more naturally established seedlings (Engel & Parrotta, 2001). However, the method is often regarded as unreliable, due to many factors that limit germination and seedling establishment, such as lack of favourable micro-sites for germination (De Steven, 1991), seed predation (Hau, 1997), weed competition and unsuitable seed types (Cole et al., 2011; Doust et al., 2008). It has been suggested that direct seeding is a more efficient way to enrich an existing system (Cole et al., 2001).

Today, more and more restoration projects are conducted worldwide (Ruiz-aen & Aide, 2005; Sayer et al., 2004) and many new techniques have been created (e.g. seed rain management or promotion of natural regeneration) (Rodrigues et al., 2010), especially low cost technique that able to apply in large scale, however, there are still many gaps in the knowledge, especially with regard to the development of a stronger theoretical base for ecological restoration (Palmer et al., 2006).

1.4 Direct seeding as a tool for forest restoration

Over the last 50 years, direct seeding has gained in importance, especially in North America and China, where large area have been direct seeded from helicopter or airplanes (Ochsner, 2001). Aerial reseeding is often used in wildfire devastated areas (USDA Forest Service, 2001); it is used to rapidly restore plant cover where severe wildfire has killed vegetation and consumed organic soil cover (Robichaud et al., 2000) and, in some cases, to inhibit the invasion and spread of exotic plant species (Beyers, 2004; Floyd et al., 2006). Seeding is the most widely used post-fire stabilization treatment, but its effectiveness for increasing plant cover has been variable (Robichaud et al., 2000).

In addition, direct seeding is often used when mine-spoils are being vegetated in order to control erosion in the short term and provide forest products in the long term. For example, in northern Australia direct seeding of mine-spoils was carried out using aerial seeding of a mixture of 30 native tree species and fertilizer (Foster & Dahl, 1990); herb seeds could be subsequently added in order to provide ground cover as found in a field trial in India (Jha & Singh, 1993). However, direct seeding for mine rehabilitation can be somewhat hit and miss if not carefully planned and implemented, or when unpredictable weather conditions follow seed spreading. A number of important aspects need to be taken into account to increase the chances of success when seeding, such as seed supply, seed treatment, ecosystem succession, seeding rate, seed spreading, timing of seeding and spreading vegetation (Mine Rehabilitattion Working Group, 2006).

More precise application or seed spreading can be achieved by hydroseeding or hydromulching but the amount of material required is expensive and these techniques require specialized equipment. Such techniques were developed in the late 1970s and involve seeds being "sprayed" in a slurry combined with processed woodchip fibers and other optional enhancements i.e. fertiliser and a tackifying agent, to speed the growth and prevent seed/slurry runoff or pooling (USDA Forest Service, 2001).

Mechanical seeder is another way to sow the seeds. Modified agricultural seeders are used to place the seeds with a certain spacing, and most importantly, place them in the soil; the seeds are thereby better protected from predators and have better conditions for germination and survival (Ochsner, 2001). The study of Montalvo (2002) indicated that small-seeded species had higher density in imprinted and hydroseeded than drilled treatments, whereas large-seeded species had higher density in imprinted and drilled than hydroseeded treatments.

However manual methods usually generate the best results overall, including hand-sowing or dibbling (where a small hand-tool is used) (Ochsner, 2001). For hand-sowing, the seed spots are prepared with a hole and the seeds are placed either on top or in the ground at a depth depending on the type and size of the seeds. Dibbling is commonly used where there is little competition from weeds, for example on abandoned areas, under forest canopy (Negreros & Hall, 1996) or on already prepared seed spots (Noble, 1985). The study of Doust et al. (2006) showed that higher establishment rates occurred when seeds were buried, while broadcast sowing resulted in very poor seedling establishment.

The studies of direct seeding in temperate forests have been highly concentrated on pine, spruce, ash, oak and beech. Many studies focused on effects of sowing date, site preparation, distance on establishment, maintenance after sowing and surrounding environments on germination, survival and recruitment rate on direct seeded seedlings (Birkedal et al., 2010; Jinks et al., 2006; Löf et al., 2009; Nilson & Hjalten, 2003).

Diverse groups of plants have been used for direct seeding in the tropics but only few studies had been reported (Ochsner, 2001). Among direct-seeded species, there are two major functional groups that often been referred, pioneer and climax species. Despite this evidence, small-seeded pioneer species have more commonly been used to restore forest ecosystems, because they occur naturally at the early stages of succession (Balandier et al., 2009; Engel & Parrotta, 2001; Garcia-Orth & Martínez-Ramos, 2008; Sun et al., 1995). The pioneer species could germinate and establish quickly in the open areas ((Schmidt, 2007; Snell & Brooks, 1997; Sun et al., 1995). The faster trees cover and shade other plants, the higher are the chances are for survival. Small seeded early successional species is therefore likely to have a higher chance of success, especially where the weed is minimized (Doust et al., 2008).

On the other hand, late-successional species generally produce large seeds (Slik, 2005); they were classified as a good establishment on degraded area (Doust et al., 2008). This may be because the high energy reserves contained within larger seeds allow them to remain viable for longer in unsuitable environments (Muller-Landau, 2010; Osunkoya et al., 1994) but due to their slow growth characteristic, this might be a barrier for them to win in competition with the weeds. However, reintroducing late-successional species in early-successional environments may help to bypass this low-diversity stage by overcoming dispersal limitation (Martinez-Garza et al., 2005).

Legume species is another group of plants that been selected for direct seeding. They have been successfully established in degraded areas and have exhibited high growth performance because they can fix atmospheric nitrogen using symbiotic bacteria (Rhizobium) in their root nodules (Engel and Parrotta, 2001).

Pre-sowing seed treatments, such as scarification, sulphuric acid, boiling water and cold stratification, has been employed to accelerate germination and shorten dormancy.(Huang & Gutterman, 2000; Ren & Tao, 2004; Yang et al., 1999). The seeds require seed treatment before sowing to decrease the time available for seed predation to occur, however a certain treatment without burial did not accelerate germination in the field due to desiccation (Woods & Elliott, 2004). Suitable pre-treatments to enhance germination rates were not known for most of the tropical species (Sautu et al., 2006). However for some species, such as *Alphitonia petriei* (Rhamnaceae), which is commonly used for direct seeding in Australia; boiling water and soaking for 48 hours has been applied before sowing in the field (Doust et al., 2006, 2008; Snell & Brooks, 1997; Sun et al., 1995).

Seed coating (with fertiliser, fungicide and/or insecticide, etc.) is another approach to increase possibility for the seeds to establish successfully. The technique of coating seeds began in New Zealand with the purpose was to facilitate aerial distribution and high germination of seed on rough terrain and unsuitable soil. The technology evolved in the United States to further enhance germination characteristics and facilitate ground-based mechanical planting. Coating is now a method used worldwide for enhancing germination, facilitating accurate aerial spreading, and increasing mechanical planting efficiency (USDA Forest Service, 2001). It has also been used with direct seeding , for example in tropical northern Australia, however it is not recommended for *A. petriei* because seeds coated with fertiliser, fungicide and insecticide of this species showed lower germination percentage than uncoated seeds in both glasshouse and field conditions (Sun et al., 1995).

Target sites had been fenced to provide protection against grazing (Engel & Parrotta, 2001; Sun et al., 1995), and fire lines establishment is needed if fire occurs in high frequency (Engel & Parrotta, 2001). Existing weed growth at each of the study sites is often cleared via mechanical and/or chemical treatments prior to sowing; glyphosate is commonly used at the beginning and a few times afterward (Doust et al., 2006, 2008; Engel & Parrotta, 2001; Snell & Brooks, 1997; Sun et al., 1995). Post sowing site management, such as removal of weeds had been suggested to be considered (Doust et al., 2008), especially during early establishment (during the first 2 years after sowing), for example, additional spot application of the herbicide, manual weeding around seedlings, or setting ant traps to reduce herbivory damage to seedlings (Engel & Parrotta, 2001).

Fertiliser (a mixture of ammonium nitrate and ammonium sulfate) had been applied with the seed mix (mostly fast-growing non-native grass species are used) or after sowing; the combined treatment has been mentioned to be a potential erosion control in USA (Dodson & Peterson, 2009; Robichaud et al., 2006). Slope stabilization treatments are frequently applied following high severity wildfires to reduce erosion, protect water quality, and mitigate threats to human life and property. The result from Dodson and Peterson (2009) showed that seeding and fertilisation did little to reduce erosion hazards, however the fertiliser treatment significantly increased the mean canopy cover in the fourth year of the study of Robichaud et al. (2006).

The potential advantage of direct seeding over other plantation establishment techniques included cost savings associated with nursery care and planting. However, significant disadvantages that usually outweigh those mentioned advantages i.e. typically very low germination survival percentage, and/or increased weeding costs to overcome high mortality from weed competition (Engel & Parrotta, 2001). Evaluations of costs for establishment and maintenance of direct seeding should help on planning efficient approach for restoration project. The study of Engel and Parrotta (2001) reported that direct seeding could save about 70% for establishment and maintenance for the first 2 years compared to planting the nursery-grown seedlings per hectare in Brazil. In northern Thailand, Tunjai (2005) indicated that establishment of direct seeded plants can reduce cost by about 50%, compared with nursery-raised plants per 0.16 hectare since costs of most activities in the nursery, for transport and for casual labour was reduced. In addition, previous studies in Australia indicated that direct seeding may reduce costs by as much as 90% compared to the establishment of nursery-grown seeding (Sun & Dickinson, 1996; Thompson, 1992).

1.5 Case studies of success and failure with direct seeding

To date, direct seeding has been developed in several regions for forest restoration but most of the application has not been applied beyond an experiment for both temporal and spatial scale. Direct seeding in the tropics has been less well-reported, but it has been carried out many times without the results ever being academically published (Ochsner, 2001). For example direct seeding plots were tried in Cambodia under cooperation between local and international organizations (Cambodia Tree Seed Project, 2004).

A notable restoration program of open caste mine sites has been developed since the early 1980s by a Brazilian bauxite mining company, operating at Trombetas in Para′ State in central Amazonia. Direct seeding was one of the reforestation methods applied, 48 species of short-lived, native early successional trees were planted over a 17-ha area in 1986. Direct seeding was suitable (with survival rate $\geq$ 75%) for 21% of species tested. Forest structure (canopy cover, tree basal area, and litter and humus depths) was broadly similar among restoration treatments; the proportion of total basal area was 84% which was slightly higher than the mixed native species planting (80%). Direct seeding resulted in significantly higher tree population densities than both natural regeneration and mixed commercial species planting; and the average density of larger stems ($\geq$2 m tall) was the most highest (mean: 0.54 ± 0.03 SE/m^2). Despite these highly favorable characteristics, the direct seeding treatment has two notable disadvantages; the dominance of their basal area (>50% of the total stand basal area) by very short-lived (<20 years) species. A second disadvantage is the density of grasses which possibly slow forest succession (Parrotta & Knowles, 1999, 2001).

Current environmental legislation in Brazil aimed at reversing deforestation trends and protecting the region's agricultural soils, rivers, and their hydroelectric generation capacity, requires the restoration of forest on 20% of the total land area on all rural properties, particularly in riparian sites. Direct seeding had been considered as a part of a larger study evaluating several silvicultural techniques for restoring tropical moist forest on abandoned agricultural lands in southeastern Brazil. Of the five species planted, two legume species (*Enterolobium contorstisiliquum* and

Schizolobium parahyba) showed good germination, seedling survival, and early growth rates, averaging 4.1 – 4.6 cm stem diameter and 1.5 – 1.7 m height growth during the first 2 years after sowing. Natural regeneration of native forest species within the direct-seeded plots was significantly greater than in unplanted control plots (Engel & Parrotta, 2001).

Seeding is widely used across the Australian mining industry for establishing both native vegetation communities and pastures. For example, the Groote Eylandt Mining Company (GEMCO) mines manganese from a number of leases on the western coastal plain of Groote Eylandt. They started with reshaping landforms, followed by double-stripping, the return of subsoil and fresh topsoil and ripping to 1.4 metres to reduce compaction. Vegetation establishment involved, using seed and planting procedures designed to return the maximum number of plant species at densities that closely represent those found in the adjoining analogue forests. So far, about 25 species of local trees and shrubs have been collected from the leases for direct seeding or the growing of seedlings for wet season planting (Mine Rehabilitattion Working Group, 2006).

Similarly, direct seeding has been used as a method of revegetating degraded land in Australia; the establishment of the pioneer rainforest species *Acacia aulacocarpa*, *Alphitonia petriei* and *Omalanthus populifolius* by direct seeding increased the regeneration of secondary rainforest species in terms of numbers of regenerating species, however there was no significant difference compared to tree planting (Snell & Brooks, 1997).

In U.S., the Surface Mining Control and Reclamation Act of 1977 requires that coal mine sites are reclaimed to establish vegetative cover that is diverse, native, and capable of plant succession. However, many grass species commonly planted in reclamation have aggressive growth habits that lead to their dominance in coal mine plant communities. Alternative mixtures of grass species were therefore chosen specifically for low growth habit and low-density turf. Mixture of grass species with low competitive were broadcast seeded in plots, the commonly used reclamation woody species such as *Robinia pseudoacacia*, *Populus tremuloides*, *Quercus rubra* and *Pinus resinosa* were subsequently direct-seeded at the center in the grass plots. Very few seedlings of woody species survived through the end of the second growing season. There were also no surviving seedlings in the unseeded control plots. Although there were initially seedlings in control plots, it is possible that the low vegetative coverage in control plots allowed the seedlings in these plots to be exposed to greater levels of sun and high temperatures and thus resulted in greater mortality (Halofsky & McCormick, 2005).

In Mexico, natural regeneration is frequently slow in abandoned areas. Direct seeding of mature-forest species (*Brosimum alicastrum*, *Enterolobium cyclocarpum*, and *Manilkara zapota*) was carried out as a restoration strategy in sites previously used for slash-and-burn agriculture in semi-evergreen, seasonal forest. Sites were classified in three forest ages; recently abandoned (<5 years), young successional forest (8–15 years), and reference forest (>50 years). Overall, an average of 5–41% of planted seeds germinated, and 3–35% were present through the seedling stage. Of the seeds that germinated in the 8–15 years sites and the reference forest, 58–95% of the seedlings survived through the end of the study. Direct seeding these mature-forest species after the first few years of natural succession could be a successful strategy to accelerate and guarantee their establishment (Bonilla-Moheno & Holl, 2010).

In addition, direct seeding of native pine (*Pinus massoniana*) was used as the main afforestation method in Hong Kong. Direct seeding was first done by spot sowing in prepared pits but in 1883 and 1885, experiments showed that much better results were obtained from broadcasting (Hau, 1999). Moreover, Flippance (1939) noted that direct seeding of *P. massoniana* was gradually found more effective than planting bare-rooted pine seedlings raised in the nursery. However, Ford (1883) reported that on steep slopes, direct seeding appeared less promising due to the stronger drying influence of the sun and heavy rain tended to wash away the loose soil together with the seeds.

Failures of direct seeding are usually influenced by its disadvantages i.e. typically very low germination survival percentages resulting in either inadequate plantation stocking, poor early seedling growth, and increased mortality associated with weed competition, in addition to increased susceptibility to poor weather conditions (Evans, 1982). Direct seeding failures greatly outnumber successes and they are rarely reported (Engel & Parrotta, 2001), for example, 3 out of 6 species (*Artocarpus lakoocha*, *Casearia grewiifolia* and *Eugenia cumini*) failed to germinate in the degraded dry dipterocarp forest in northern Thailand due to unsuitable species used. Similarly, one species (*Trewia nudiflora*) showed high germination (70-80%) but only few seedlings survived over one year after sowing (Tunjai, 2005).

1.6 Reforestation in southern Thailand

The southern forests are disappearing, similar to other parts of Thailand. The tropical semi-evergreen forest has covered about 29,626 km^2 (41.89% of land area) in 1961, and decreased to be 12,125 km^2 (17.15%) in 1998 (Royal Forest Department, 1998). Peat swamp forest covers about 647 km^2; and there is sparse information on destruction and degradation of the beach forest; this forest has been gradually converted to be the hotels and resorts during the peak of tourism promotion, and also to support industrialization such as the construction of power plants and/or gas separation plants (Boonsophon, 1999; Sakoolthap, 2000).

Deforestation in this region has two major causes; increasing population and agricultural land needed had caused forest disappearing in the early phase, while the national laws and policies in relation to socioeconomic is the main cause in the later phase (Ganjanapan, 2000; Jamarik & Santasombat, 1993; Pinthong, 1992). The southern forest has significantly decreased since Siam signed the Burney Treaty with the British in 1826 and the Bowring Treaty in 1855. These agreements elaborated and liberalized trade rules and regulations by creating a new system of imports and exports; the main exported products were rice, rubber latex, tin and teak. The central government adopted top-down system to control resources management throughout Thailand. The Royal Forest Department was established in 1896 to control the utilization of forest resources and locate the forest areas that belong to the government. Forest concessions started in the north of Thailand with international cooperation and then continually expanded southward (Kaewsin, 2006).

After 1957, there were several timber concessions active in the south. Especially after the big storm in 1962 that caused huge forest destruction in Nakhon si Thammarat and Surat Thani, there was a peak period for timber production and sawmill business in the region. The condition of forest concession has changed from bid contract to provincial contract in 1968 and it caused the highest record of forest concession during 1973-1974 which leaded to rapidly decreasing in forest area. Deforestation rate has dramatically decreased about 83% after the concession was banned in 1989 (Kaewsin, 2006).

On the other hand, planting of monoculture crops such as rubber trees and oil palms has caused further deforestation and forest degradation. In 1912, the government of Siam encouraged Chinese investors to plant rubber trees for protecting the land from British colonization. During that time, the rubber plantation had been established between Padangbeza and Sadao in Songkhla for about 80 km^2 and it had increased to be 16,994 km^2 (84% of total rubber plantation) throughout the southern region in 2003 (Kraiyoonwong, 2008).

Oil palms were first planted in Thailand at Ko Hong Rubber Experiment Station in Songkhla for decoration purpose in 1929. The government initially supported planting oil palms for economic purpose in Satun and Krabi in 1968, about 64 km^2 in total area. Interest in planting oil palm increased every year. Palm oil refineries were established in 1974; shortly afterwards palm oil became entered the cooking oil market. Moreover, since the energy crisis interest in palm oil production has increased. There is a national policy to promote oil palm plantation as the important body of biodiesel production. Recently, oil palm plantations have been defined as economic forests by the government. Plantations covered about 3,200 km^2 in 2003 and had increased to 4,320 km^2 in 2004 (34% increasing within a year) (Kraiyoonwong, 2008; Rubber Research Institute of Thailand, 2011).

The crucial turning point of forest resource management, from economic to conservation purposes, was influenced by two major events; firstly the big flood at Katoon, Nakhon Si Thammarat in 1988; and secondly the protest against forest concessions in the north and northeast of Thailand during 1986-1988. Both events led to a logging ban in 1989 (Kaewsin, 2006).

Reforestation in southern Thailand has been performed by two major groups, the governmental and the private sectors. Most planting activities run by the government are held on the special days, such as the King's and the Queen's Birthday; available seedlings from nearby seedling propagation station are planted. The weak point of previous reforestation projects is that non-native species were used and no monitoring system was implemented. Nevertheless, guidelines for restoring watersheds were published by the Protected Areas Regional Office 5 (Nakhon Si Thammarat). Planting of five main native trees species is recommended as well as establishing Vetiver grasses, check dams and fire breaks employed together as a package. Site preparation i.e. weeding and digging the holes, will be carried out beforehand, seedlings will be harden 1-2 months before planting, density and maintenance period will be varied by the level of current disturbance (Protected Areas Regional Office 5, 2010). Unfortunately, no results achieved by this technique has been published.

For NGOs and academic sectors, an outstanding example has been performed by the cooperation between national (Forest Restoration Research Unit (FORRU) and Bird Conservation Society of Thailand (BCST)), international NGOs (The Royal Society for the Protection of Birds - RSPB) and local communities in Krabi. A project on restoring the habitat for Gurney's Pitta had been established in 2005 to 2011. So far, 60 indigenous forest tree species were tested in field trials covering 7 ha from 2006 to 2010 (Personal Communication). The field performance of tree species is currently being monitored and FORRU has produced a list of potential framework tree species to promote recovery of Gurney's Pitta habitat. In recently deforested sites, FORRU's preliminary trials of Assisted Natural Regeneration (ANR) have produced excellent results in stimulating the recovery of lowland tropical rainforest (FORRU, 2008b).

In addition, the target ecosystems for restoration in the Pak Phanang Watershed have been prioritized by the Institute of Research and Development, Walailak University; Nipa palm forest got the highest priority, next is mangrove forest, peat swamp forest and watershed forest (Natural and environment management research group, 2010). Unfortunately, except mangrove forest, there is no existing publication related to the restoration in those mentioned ecosystems.

Several communities are working on conservation issues, such as the Sago Forest Conservation Club in Trang which has documented plant diversity in their conserved Sago palm forest and initiated educational activities for raising awareness among local people (Worapornpan, 2007). In addition, a group of local villagers in Songkla has planted native tree species for restoring the beach forest nearby their settlement. Fast-growing pioneer trees are firstly planted to create sufficient shade for shade-tolerant species. Intensive maintenance is necessary during early establishment since sand cannot hold efficient water for seedlings, then medicinal herbs will be additional planted when suitable conditions are achieved (Kai, 2008).

Very few studies are available in the literature concerning forest restoration ecology in southern Thailand. Lacking of scientific research is the weakest point in restoration. The planting might be useless without considering the original ecosystem; therefore native species should gain more attention in the context of phenology and propagation. Despite several planting activities in different ecosystems, none of them has been evaluated costs in relation to the outputs. More alternative techniques that could be applied in a large scale with cost effective should be further investigated. A comprehensive restoration strategy is currently lacking, partly because unconnected policies between governmental units.

1.7 Research objectives of this study

In previous studies, direct seeding has been studied in a number of temperate forests and some tropical forests including rehabilitation after mining. Although, there is an increasing interest in low cost methods that can be applied on a broad scale for restoration (Doust et al., 2008), no one has developed a suitable systematic screening method for species selection for forest restoration projects in Southeast Asia.

Despite an urgent need of appropriate methods for restoration, there have been few studies on restoring indigenous species in Thailand. No direct seeding studies have been reported in southern Thailand. There has been no systematically screening of species and proper tests to find effective techniques for direct seeding. For certain species, suitable sowing time, method and maintenance could offer an effective, cost-efficient alternative to out-planting nursery-raised seedlings for forest restoration (Woods & Elliott, 2004). Thus suitable direct seeding methods and species will help to create an effective tool for restoration, and to understand patch dynamic on abandoned areas, especially in southern Thailand, with regards to different climate patterns.

Studies on tree phenology are essential for forest restoration programs to determine when fruit and seeds develop, ripen and are dispersed. They can be used to determine optimal seed collection times throughout the year for individual tree species (FORRU, 2008a) and describe seasonal variability in the availability of food for exist wildlife (Wallace & Painter, 2002). A phenological study of lowland forest in southern Thailand was therefore implemented to describe annual patterns and intraspecific variation between sites with different precipitation regime, and to target the potential candidates for direct seeding (see chapter 3).

Previous studies showed that various seed traits are likely to affect germination and dormancy and therefore contribute significantly towards seedling establishment (Cervantes et al., 1996; Doust et al., 2006; Liu et al., 2007; Tunjai, 2005; Yu et al., 2007). If easily-measured seed traits can be used to predict which tree species can be successfully established by direct seeding, this will help to develop a cost-effective technique for restoration. Direct seeding experiment was thus conducted to study the effects of seed traits (size, shape, seed coat thickness and moisture content) on dormancy, germination and seedling establishment in the harsh conditions, and to explain the associations between seed size and other life-history attributes (see chapter 4).

Although seeds may be safely sown, natural regeneration in degraded areas is a slow process, often due to unsuitable conditions for seed germination and seedling establishment (Holl et al., 2000). Experiments were therefore conducted to determine the effects of sowing and management regimes on the germination, establishment and growth performance of direct-seeded species, and to determine barriers that might slow down successional process on abandoned areas (see chapter 5).

The potential advantages of direct seeding over other plantation establishment techniques (i.e. planting of nursery-grown seedlings, wilding or rooted cuttings) include cost savings associated with nursery care and planting, as well as the naturally established seedlings (Engel & Parrotta, 2001), while the significant disadvantages can outweigh these advantages include low germination and survival percentages, and poor early seedling growth (Evans, 1982). A seedling transplantation experiment was therefore carried out to compare the growth performance of nursery-grown and direct-seeded seedlings in the field. Also cost-evaluation of these techniques was carried out (see chapter 6).

Species performance regarding taxonomic relations (Ibarra-Manríquez et al., 2001) and ecological strategies (Wishnie et al., 2007) are varied depend on different environments. Understanding this relationship would assist on developing efficient tool in species selection process for restoration by direct seeding, and to build up the knowledge on natural regeneration with human intervene on degraded areas in southern Thailand. An analysis was carried out using the data from Chapter 4 and 6 to find out if some species traits had contributed to higher successful colonisers on abandoned areas, and higher achievements of direct seeding on different sowing time (see Chapter 7).

Chapter 2

Site description

2.1 Southern Thailand

2.1.1 Geography

Southern Thailand is approximately situated between 6° to 11°, Northern latitude and 98° to 103° Western longitude. Its coastlines face two different seas: the eastern is exposed to the Gulf of Thailand and the western to the Andaman Sea. The Gulf of Thailand, an inlet of the South China Sea, has a coastline along the southern region stretching for approximately 930 km. Many rivers discharge water and sediment into the gulf. The Andaman Sea, which connected to the Indian Ocean, has a 937 km long coastline. The geomorphology of the gulf coast is characterized by a long and wide mainland beach of sand and dunes, with lagoons, bays and spits. Pocket beaches, extensive and well preserved tidal flats, cliff coasts and numerous islands dominate the Andaman coast (Thampanya et al., 2006).

There are many hills and mountains bordered by the seas. The Tenasserim Range located on the west, in the upper part of this region. Closely, the Phuket Range located southward from Chumphon to Phang Nga. In the middle part, next to the Phuket Range, there is the Nakhon Si Thammarat Range located long from Surat Thani, through Krabi, Nakhon Si Thammarat, and end at Satun. The far south mountain range is Sankalakhiri Range, which forms the border between Malaysia and Thailand (Changpeuk, 1996). Southern Thailand is composed of 14 provinces; 8 provinces on the east coast (Chumphon, Surat Thani, Nakhon Si Thammarat, Phatthalung, Songkhla, Pattani, Yala and Narathiwat) and 6 provinces on the west coast (Ranong, Phang Nga, Krabi, Phuket, Trang and Satun).

2.1.2 Climate

The area has a tropical climate with two monsoonal winds: the northeast (NE) during mid October to March and the southwest (SW) during May to September. The NE wind has a longer fetch and mainly generates waves along the Gulf coast. Highest waves along the Andaman coast are generated by the SW monsoonal wind. Peaks in wind and wave intensity caused by the passing cyclones frequently accompany the retreat of the monsoon during October to November (Vongvisessomjai et al., 1996). The annual rainfall of the Southern region is higher than in other parts of Thailand and highest precipitation occurs on the Andaman coast (2100-4000 mm y^{-1}) whilst it ranges between 1600 and 2400 mm y^{-1} on the Gulf coast (Thampanya et al., 2006).

2.1.3 Vegetation

Most terrestrial forests in southern Thailand are classified as tropical rain forests which commonly have three layers; emergent, canopy and understory. Emergent layer consists of large trees (>25 m), cauliflory is common feature. Dense canopy is found under the emergent at about 10 – 25 m and with smaller understory and seedlings on the ground. Dipterocarp species are common in the emergent layer; they cover shade-dwelling trees below, and diverse species of shrubs, herbs, rattans, palms and lianas (Santisuk, 2006).

There are two types of tropical evergreen rain forest in Thailand; the lower tropical evergreen rain forest is formed in lowland area (<600 m elevation), and the upper tropical evergreen rain forest is found in the area between 600 – 900 m elevation (Sukwong, 1993). The structure of southern forests can be subdivided into two types; the tropical semi-evergreen rain forest is common in this region, the north of Kedah state i.e. this forest formation is found on the Tenasserim Range, Phuket Range and Nakhon Si Thammarat Range. The tropical evergreen rain forest is another one found on the south of Kedah state and southward, or on Sankalakhiri Range and Malaysian forest complex (Sawangchote, 1997; Whitmore, 1990).

However, there is no definite agreement on a definition of rain forest. The basic concept of rain forest include a tall, evergreen with over 1800 mm of rainfall per year and no or only a very short (up to 4 weeks) dry period. With this concept, Maxwell and Elliott (2001) mentioned that the climatic and vegetational conditions throughout most of Thailand cannot realistically be considered rain forest, except the southernmost provinces that would be marginally included. Seasonal evergreen forest would be the most appropriate terminology for the forest there.

Swamp forest occupies coastal wetlands or river estuaries with mud. There are two types of the swamp forest; the peat swamp forest and the freshwater swamp forest. Evergreen tree species are dominate in the peat swamp forest, this ecosystem has waterlogged condition throughout the year. The litter turns into peat which has continued to form up until the present day. In contrast, the freshwater swamp forests are formed on lowland area along the river bed, and there is no litter accumulation in this ecosystem (Santisuk, 2006).

Moreover, another terrestrial ecosystem in southern Thailand is the beach forest; it could be found on the coastal area with soil or sand bed, however it is influenced by sea mist and wind. The beach forests are formed on both the east and the west, and also on the island shoreline (Sakoolthap, 2000).

2.2 Study sites

2.2.1 General description

The study sites were located in two provinces in southern Thailand. Krabi is one of the southern provinces, at the shore of the Andaman Sea. Most notable are the solitary limestone hills, both on the land and in the sea as islands. The limestone hills contain many caves, most having beautiful stalactites and stalagmites (Wikipedia, 2011a). The mean temperature was 26.9° C, with monthly averages ranging from 26.3° C in December to 27.9° C in April. Mean annual precipitation (1989-2008) was 1,804 mm, most of which falls between May and October (Figure 2.1a).

Nakhon Si Thammarat is located on the shore of the Gulf of Thailand on the east side of the Malay Peninsula. The terrain is mostly rugged hilly forest area. It contains the highest elevation of southern Thailand, the Khao Luang with 1,835 m (Wikipedia, 2011b). The mean monthly annual temperature was 27.5° C, ranging from 25.8° C in December to 28.5° C in May. Mean annual precipitation (1989-2008) was 1,941 mm, with the wet season extending from October to December (Figure 2.2a).

Long-term climatic data has been collected by the Thai Meteorological Department at station 566003 (Khlong Thom district) and 552005 (Thasala district) for Krabi and Nakhon Si Thammarat sites respectively. Different timing of the wet and dry seasons between the sites is caused by two monsoonal winds which blow from the northeast for half the year (November to April), then reverse and blow from the southwest (May to October). Southwest winds cause a wet season at Krabi, whilst northeast winds cause a wet season at Nakhon Si Thammarat. The geological map indicated sedimentary and metamorphic rocks are dominant in both Krabi and Nakhon Si Thammarat provinces (Department of Mineral Resources, 2007a, 2007b).

2.2.2 Site selection

For chapter 3, the study was conducted in two sites; around Khao Nor Chuchi in Krabi province on the west coast, and the Walailak University campus in Nakhon Si Thammarat province on the east coast of southern Thailand. The small forest patches that remain around Khao Nor Chuchi in Khao Pra Bang Kram Wildlife Santuary and in the adjacent reserved forest and non-hunting area of Khlong Thom District in Krabi, are probably the most significant remnants of lowland tropical evergreen forest still surviving in Thailand. This type of forest has been mentioned to be one of Thailand's rarest and most endangered wildlife habitats (Elliott et al. 2008), and it is the home for the rarest bird of Thailand, Gurney's Pitta (*Pitta gurneyi*), now its population has reduced to about less than 20 birds (Sribuarod, 2011). In addition, the remnant of forest patches in Walailak University was selected because it exists in similar latitude and elevation, and possibly last long until the end of observation.

During the study in Krabi, most rain fell during May to October (2009-2010), annual precipitation was 1,608 mm (Figure 2.1b). Remarkably, at Nakhon Si Thammarat, there was a marked peak of rainfall in August before two months of dropping rainfall below 150 mm, and then the second moderate peak in November to December, total annual rainfall was 2,392 mm (Figure 2.2b). Climatic data during the study period was collected by the Thai Meterological Department at Krabi

International Airport and Walailak University for Krabi and Nakhon Si Thammarat sites respectively.

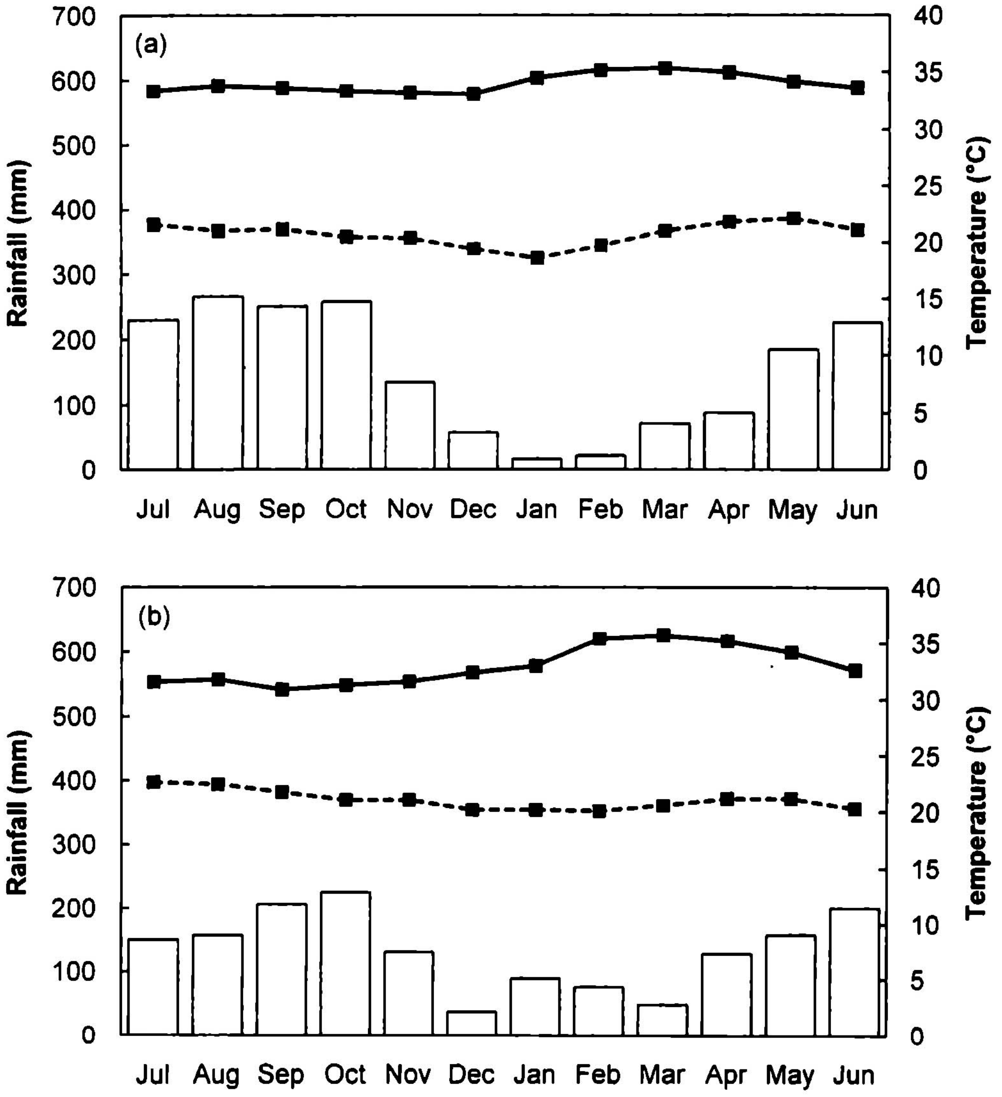

Figure 2.1 Total monthly rainfall, and mean maximum and minimum temperature at Krabi; (a) 1989-2008 and (b) 2009-2010

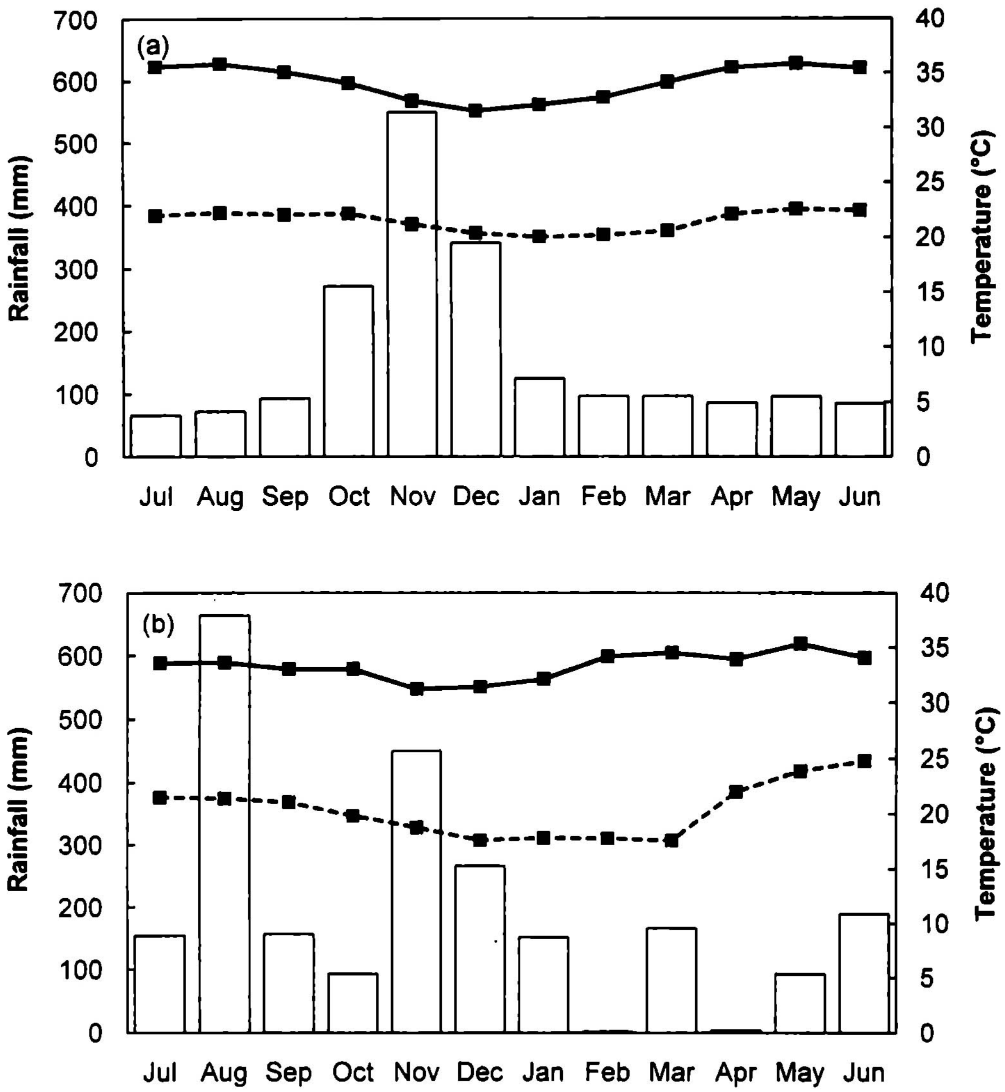

Figure 2.2 Total monthly rainfall, and mean maximum and minimum temperature at Nakhon Si Thammarat; (a) 1989-2008 and (b) 2009-2010

For chapter 4 to 6, the experiments were also carried out in two southern provinces. The Krabi site was a 100 m x 40 m gap situated next to an oil palm plantation at about 80 m elevation at the base of a hill slope and was dominated by the grass, *Imperata cylindrica* (L.) P. Beauv. (Gramineae) in the Khlong Thom Nuea Tambon Administration Organization area. The site was an abandoned former oil palm plantation that remained dominated by grasses for the last 10 years. Similarly, the Nakhon Si Thammarat site was also an abandoned area but from rice farming since last 15 years, close to secondary forest, at about 100 m elevation in the Farm University, Walailak University campus. The site was dominated by the herbaceous weed *Chrysopogon aciculatus* (Retz.) Trin. (Gramineae). Both sites were selected because there were high confident of continuity without further disturbances throughout the study.

Primary, evergreen, seasonal, hardwood plus bamboo forest on sandstone bedrock is present adjacent to Krabi site to the summit of Pan Din Samur (about 175 m elevation), some of it very degraded (Maxwell, 2009). Unfortunately, there was no publication referring to previous forest type in Nakhon Si Thammarat site at Walailak University Campus. However it could be called mixed evergreen plus deciduous, plus bamboo forest following the study of Maxwell and Elliott (2001) which they referred to distinctly seasonal forest type, at sea level to 1000 m elevation. Small patches of this forest type, secondary growth, were sparsely distributed in Walailak University Campus.

Geologically, Thailand consists of rocks range in age from Precambrian to Quaternary. Sedimentary rocks; terrace and colluvial deposits (pebble, gravel, sand, silt and clay), were found in Krabi site while sedimentary and metamorphic rocks (beach and delta deposits) were found in Nakhon Si Thammarat site (Vimuktanandana, 1985a, 1985b).

Soils in both sites are similar with sandy-clay texture; less than 2% of the organic matter. Soil pH is about 5 in both sites and bulk density ranged from 0.68 cm-3 (in Krabi) to 0.80 g cm-3 (in Nakhon Si Thammarat). Soil analyses were carried out by the Center for Scientific and Technological Equipments, Walailak University (Table 2.1). Nursery experiments were carried out at the same climate and elevation to both sites.

Table 2.1 Soil properties in both study sites

	Study sites	
	Krabi	Nakhon Si Thammarat
Soil texture [a]	%Clay = 35.22 %Silt = 18.31 %Sand = 46.47	%Clay = 33.89 %Silt = 18.32 %Sand = 47.80
pH [b]	5.2	5.1
N [b] (%)	0.19	0.23
P [b] (%)	0.01	0.01
K [b] (%)	0.56	0.44
Organic matter [c] (%)	1.26	1.53
Soil Bulk Density [d] (g/cm^3)	0.80	0.68

[a] Hydrometer method

[b] In house method based on AOAC official Methods of Analysis of AOAC International, 17th ed.

[c] Walkley & Black method

[d] Office of Science for Land Development, Land Development Department

Chapter 3

Phenology of lowland tropical tree species in southern Thailand

3.1 Introduction

Phenology is the study of the periodicity or timing of recurring biological events (Sakai, 2001). In the case of plants, phenological events involve flowering, fruiting, leaf flushing, abscission, seed dispersal and germination (Fenner, 1998; Sakai, 2001). These events have important effects on survival or reproductive success and are therefore important to our understanding of species interactions and community functioning (Fenner, 1998). The phenology of equatorial tropical forests is distinct from that of temperate vegetation because of the lesser degree of temperature seasonality and of associated photoperiodic and thermoperiodic adaptations (Reich, 1995). Periodic changes in rainfall caused by movements of the intertropical convergence zone often play an important role as proximate and ultimate factors for tropical plant phenology (Van Schaik et al., 1993). In addition, biotic factors, such as competition for pollinators or seed dispersers, and avoidance of herbivory, have been interpreted as ultimate causes, responsible for phenological patterns in tropical species (Elzinga et al., 2007; Lobo et al., 2003). Some studies have suggested that plant phenology is principally constrained by phylogenetic inheriance (Elzinga et al., 2007; Fenner, 1998; Wright & Calderon, 1995).

Most studies on plant phenology in tropical forests have been conducted to describe community-level patterns of leafing, flowering, and fruiting, often for purpose of resource availability for animals (Fenner, 1998; Sakai, 2001; Wallace & Painter, 2002). Most neotropical forest communities studied show flowering and fruiting peaks near the end of the dry season (Justiniano & Fredericksen, 2000). The pattern may be caused by high insolation and photosynthesis in dry seasons or by enhancement of germination and seedlings survival by adjusting fruiting to precede the beginning of the wet season (Van Schaik et al., 1993). In contrast, unpredictable fluctuations in rainfall have caused unclear annual cycles in a large portion of Asian tropical forests from Sumatran to the Philippines (McGregor & Nieuwolt, 1998; Whitmore, 1984). The phenomenon with multiyear intervals, called general flowering (GF) or mass flowering, is known from lowland dipterocarp forests in this region (Ashton et al., 1988; Fenner, 1998). During GF, many plants species, including most diptercarp species and species of other families, flower sequentially for several months, but a few flowers can be seen in non-GF periods (Sakai, 2000).

Unfortunately, accelerating land-use changes, due to expansion of monoculture plantation and urbanization, has resulted in biodiversity depletion in southern Thailand, particularly lowland tropical forest, the most species-rich of terrestrial ecosystems. Formerly widespread over most of Thailand's southern provinces, this forest type has now been fragmented and is sparsely isolated in the region. No studies on plant phenology have been conducted thus far. Therefore, there was no evidence to determine whether the lowland forests of S. Thailand were similar in their phenology to other Asian tropical forests or those from other parts of the tropics.

Studies on tree phenology are essential for forest restoration programs to determine when fruit and seeds develop, ripen and are dispersed. They can be used to determine optimal seed collection times throughout the year for individual tree species (FORRU, 2008a) and describe seasonal variability in the availability of food for exist wildlife (Wallace & Painter, 2002). Apparently, there have been no phenological studies of lowland forest in southern Thailand. The objectives of this study were (1) to describe annual patterns in phenology of lowland tropical tree species in southern Thailand, (2) to describe intraspecific variation between sites with different precipitation regimes, and (3) to target potential candidate species, which produced ripe fruits at the beginning of rainy season, for direct seeding in southern Thailand.

3.2 Materials and methods

At Krabi, a total 227 individuals of 43 tree species belonging to 25 families was monitored for one year (9 July 2009 – 30 June 2010) (Table 3.1). A minimum of 5 individual trees each species was selected except for the most sparselt distributed species e.g. 3 individuals of *A. scholaris*, *G. cowa*, *H. irya*, *I. palembanica*, *M. motleyana* and *V. odorata*, and 4 individuals of *A. leucopodium*, *C. glabrum*, *E. cerasiformis*, *G. merguensis*, *R. pinnata* and *S. indica*..

At Nakhon Si Thammarat, a total 190 individuals of 35 tree species belonging to 22 families was monitored for one year (6 July 2009 – 29 June 2010) (Table 3.1). A minimum of 5 individual trees each species were selected except for a few rare species i.e. 2 individuals of *C. castanocarpus*, *E. griffithii*, *K. andamanica* and *L. balansae*, and 3 individuals of *M. paniculatus* and *X. flavescens*.

Phenophases (flower buds, open flowers and fruits) of marked trees were recorded at three-week intervals. Each phenophase was scored for each tree using the crown density method, original devised by Koelmeyer (1959). A linear scale of 0 to 4 points was used, with 4, 3, 2 and 1 representing 100, 75, 50, and 25 per cent canopy coverage respectively. The value, 0.5 represents a tiny amount, well below 25 per cent coverage. Fruits of immature stage were regarded as young fruits. Fruits that had reached full size, but without any advertisement (colour change, smell, etc.) for dispersers were classified as mature fruits (Selwyn & Parthasarathy, 2007). Fruit ripeness was judged by colour, size, texture of embryo, dehiscence of fruit, abundance of fruit fall and any other characteristic known to be appropriate for a particular species. The same scoring system was used to score leafing or phytophases (bare branches, young leaves, mature leaves and senescent leaves).

Finally , the indices of seed production (duration, frequency, intensity, prevalence and fruit set index) were calculated for the species that flowered during observation (Elliott et al., 1994).

- Mean duration: mean length of all flowering/fruiting episodes observed for all individuals of each species
- Mean frequency: number of flowering/fruiting episodes averaged across all individuals in the species

- Intensity: mean of the maximum flower/fruit scores for all flowering/fruiting individuals converted to a percentage of the maximum value of 4
- Prevalence: number of individuals that flowered/fruited expressed as a percentage of the total sample size of each species
- Fruit set index: number of individuals fruiting expressed as a percentage of the number of individuals flowering

Table 3.1 List of 55 species observed

Species	Family	Sites observed [a]	Phenological guild [b]	Fruit type	Dispersal unit	Dispersal mode
Alstonia angustiloba Miq.	Apocynaceae	Both	Brevidecidouos	Follicle	Seed	Anemochorous
Alstonia macrophylla Wall. ex G. Don	Apocynaceae	KB	Brevidecidouos	Follicle	Seed	Anemochorous
Alstonia scholaris (L.) R. Br.	Apocynaceae	KB	Brevidecidouos	Follicle	Seed	Anemochorous
Antidesma ghaesembilla Gaertn.	Euphorbiaceae	Both	Brevidecidouos	Drupe	Fruit	Zoochorous
Antidesma leucopodium Miq.	Euphorbiaceae	KB	Evergreen	Drupe	Fruit	Zoochorous
Artocarpus dadah Miq.	Moraceae	KB	Semideciduous	Compound	Fruit	Zoochorous
Baccaurea ramiflora Lour.	Euphorbiaceae	Both	Evergreen	Berry	Fruit	Zoochorous
Bhesa robusta (Roxb.) Ding Hou	Celastraceae	NST	Brevideciduous	Capsule	Seed	Zoochorous
Callerya atropurpurea (Wall.) Schot	Leguminosae, Papilionoideae	Both	Evergreen	Pod	Seed	Zoochorous
Canthium glabrum Bl.	Rubiaceae	Both	Brevideciduous	Drupe	Fruit	Zoochorous
Carallia brachiata (Lour.) Merr.	Rhizophoraceae	Both	Brevideciduous	Berry	Fruit	Zoochorous
Castanopsis schefferiana Hance	Fagaceae	KB	Brevideciduous	Nut	Fruit	Zoochorous
Chaetocarpus castanocarpus (Roxb.) Thw.	Euphorbiaceae	Both	Evergreen	Capsule	Seed	Zoochorous
Cinnamomum iners Reinw. ex Bl.	Lauraceae	Both	Brevideciduous	Berry	Fruit	Zoochorous
Clausena excavata Burm. f.	Rutaceae	Both	Brevideciduous	Berry	Fruit	Zoochorous
Dillenia obovata (Bl.) Hoogl.	Dilleniaceae	KB	Deciduous	Follicle	Fruit	Zoochorous
Dillenia parviflora Griff.	Dilleniaceae	NST	Deciduous	Follicle	Fruit	Zoochorous

Table 3.1 (Continued)

Species	Family	Sites observed [a]	Phenological guild [b]	Fruit type	Dispersal unit	Dispersal mode
Diospyros oblonga Wall. ex G. Don	Ebenaceae	NST	Evergreen	Berry	Fruit	Zoochorous
Diospyros pilosanthera Blanco	Ebenaceae	NST	Evergreen	Berry	Fruit	Zoochorous
Diospyros venosa Wall. ex A. DC.	Ebenaceae	Both	Evergreen	Berry	Fruit	Zoochorous
Dipterocarpus alatus Roxb. Ex G.Don	Dipterocarpaceae	NST	Brevidecidouos	Nut	Fruit	Anemochorous
Dipterocarpus kerrii King	Dipterocarpaceae	Both	Brevidecidouos	Nut	Fruit	Anemochorous
Elaeocarpus griffithii (Wight) A.Gray	Elaeocarpaceae	NST	Evergreen	Drupe	Fruit	Zoochorous
Elaeocarpus stipularis Bl.	Elaeocarpaceae	Both	Brevidecidouos	Drupe	Fruit	Zoochorous
Eriobotrya bengalensis (Roxb.) Hk. f.	Rosaceae	KB	Evergreen	Pome	Fruit	Zoochorous
Eugenia borneense Miq.	Myrtaceae	Both	Brevidecidouos	Berry	Fruit	Zoochorous
Eugenia cerasiformis (Bl.) DC.	Myrtaceae	KB	Brevidecidouos	Berry	Fruit	Zoochorous
Eugenia grandis Wight	Myrtaceae	KB	Semideciduous	Berry	Fruit	Zoochorous
Eugenia papillosa Duth.	Myrtaceae	KB	Brevidecidouos	Berry	Fruit	Zoochorous
Eugenia syzygioides (Miq.) Hend	Myrtaceae	KB	Brevidecidouos	Berry	Fruit	Zoochorous
Garcinia cowa Roxb.	Guttiferae	Both	Evergreen	Berry	Fruit	Zoochorous
Garcinia hombroniana Pierre	Guttiferae	KB	Evergreen	Berry	Fruit	Zoochorous
Garcinia merguensis Wight	Guttiferae	KB	Evergreen	Berry	Fruit	Zoochorous
Horsfieldia irya (Gaertn.) Warb.	Myristicaceae	KB	Evergreen	Capsule	Fruit	Zoochorous

Table 3.1 (Continued)

Species	Family	Sites observed [a]	Phenological guild [b]	Fruit type	Dispersal unit	Dispersal mode
Intsia palembanica Miq.	Leguminosae, Caesalpinioideae	Both	Deciduous	Pod	Seed	Anemochorous
Knema andamanica (Warb.) Wilde	Myristicaceae	NST	Evergreen	Capsule	Seed	Zoochorous
Lagerstroemia balansae Koeh	Lythraceae	NST	Semideciduous	Capsule	Seed	Anemochorous
Lepisanthes rubiginosa (Roxb.) Leenh.	Sapindaceae	Both	Evergreen	Drupe	Fruit	Zoochorous
Litsea grandis (Wall. ex Nees) Hk.f.	Lauraceae	Both	Semideciduous	Berry	Fruit	Zoochorous
Madhuca malaccensis (Cl.) Lam	Sapotaceae	KB	Evergreen	Berry	Fruit	Zoochorous
Madhuca motleyana (de Vr.) Baeh.	Sapotaceae	KB	Evergreen	Berry	Fruit	Zoochorous
Mallotus paniculatus (Lmk.) M.-A.	Euphorbiaceae	NST	Deciduous	Capsule	Seed	Anemochorous
Microcos paniculata L.	Tiliaceae	Both	Brevideciduous	Drupe	Fruit	Zoochorous
Morinda elliptica (Hk.f.) Ridl.	Rubiaceae	Both	Brevideciduous	Compound	Fruit	Zoochorous
Peltophorum pterocarpum (DC.) Back. ex K. Hey.	Leguminosae, Caesalpinioideae	Both	Semideciduous	Pod	Fruit	Anemochorous
Radermachera pinnata (Blanco) Steen.	Bignoniaceae	KB	Evergreen	Pod	Seed	Anemochorous
Sandoricum koetjape (Burm.f.) Merr.	Meliaceae	Both	Evergreen	Drupe	Fruit	Zoochorous
Saraca indica L.	Leguminosae, Caesalpinioideae	KB	Evergreen	Pod	Seed	Anemochorous
Schima wallichii (DC.) Korth.	Theaceae	KB	Brevideciduous	Capsule	Seed	Anemochorous

Table 3.1 (Continued)

Species	Family	Sites observed [a]	Phenological guild [b]	Fruit type	Dispersal unit	Dispersal mode
Scolopia spinosa (Roxb.) Warb.	Flacourtiaceae	KB	Evergreen	Berry	Fruit	Zoochorous
Streblus asper Lour.	Moraceae	NST	Brevideciduous	Drupe	Fruit	Zoochorous
Vatica odorata (Griff.)	Dipterocarpaceae	KB	Semideciduous	Nut	Fruit	Anemochorous
Vatica pauciflora (Korth.) Bl.	Dipterocarpaceae	NST	Evergreen	Nut	Fruit	Anemochorous
Vitex pinnata L.	Verbenaceae	Both	Brevideciduous	Drupe	Fruit	Zoochorous
Xanthophyllum flavescens Roxb.	Polygalaceae	NST	Evergreen	Drupe	Fruit	Zoochorous

[a] Site observed; KB = Krabi and NST = Nakhon Si Thammarat

[b] Phenological guilds; Evergreen = dropping leaves less than 10% of canopy fullness; Deciduous = lose all leaves for at least one month; Semideciduous = dropping leaves at least 50%; and Brevideciduous = dropping leaves less than 50% (Eamus, 1999)

3.3 Results

3.3.1 Reproductive phenology

At the community level, an annual flowering pattern was the most common at KB (58% of observed species), whereas subannual flowering was more common at NST (51% of observed species). Three species flowered and bore fruits in every month at NST and only one species expressed a similar pattern at KB (Figure 3.1).

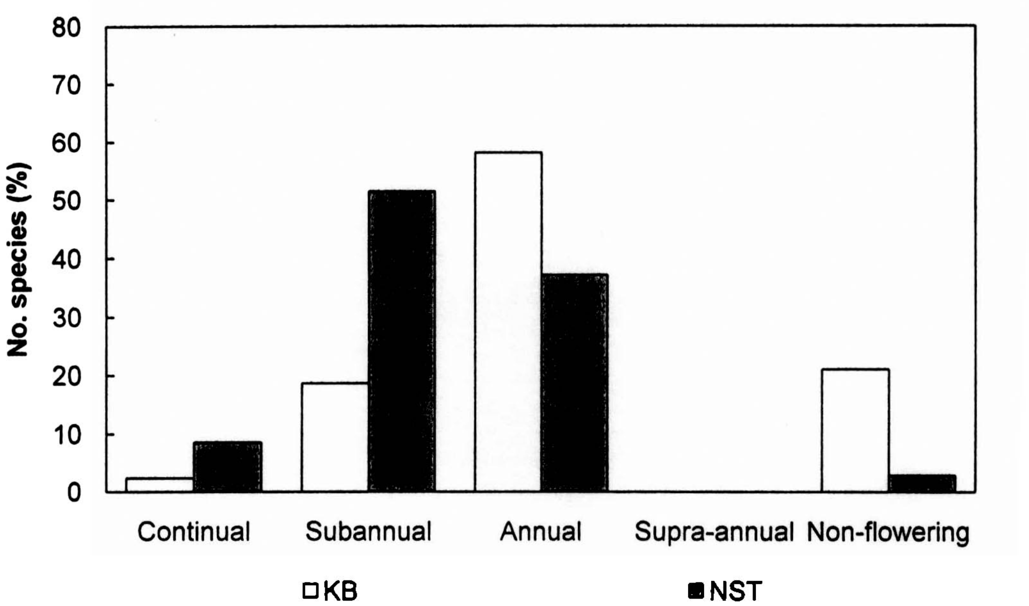

Figure 3.1 The proportion of subannual, annual, supraannual, and continual flowering types of observed tree species; KB = Krabi and NST = Nakhon Si Thammarat

The dry season was deifned as the period during which mean monthly rainfall fell below 150 and 200 mm at the KB and NST site respectively. Flowering peaked during the dry season at both sites. There was a sharp peak at the middle of dry season, plus an additional peak during the first rain in August at NST, whilst a moderate peak was discernable at KB during the dry season (Figure 3.2).

Slightly different patterns of annual fruit ripening were distinguished between the two different locations. On the west coast at KB, there were two peaks of fruit ripening, one during middle rainy season to early dry season (August -

November) and a later one near the end of dry season (March). There were also two peaks of fruit ripening found on the east coast at NST, a remarkable peak during the first rain in the year (July - September), one with smaller quantity during dry season (March) (Figure 3.3).

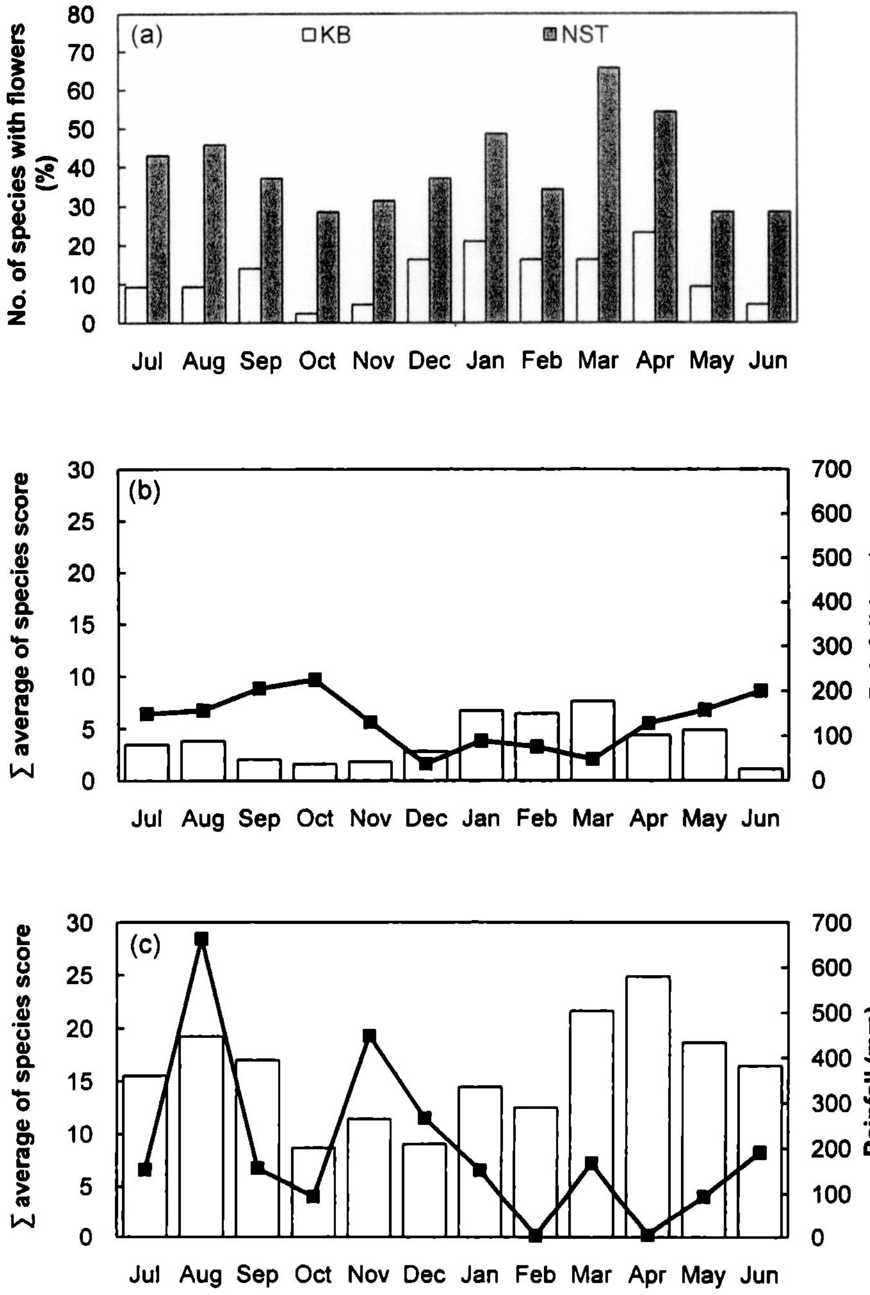

Figure 3.2 Observed patterns of community flowering; (a) no. of species with flowers, and sum average of species score at (b) KB = Krabi and (c) NST = Nakhon Si Thammarat

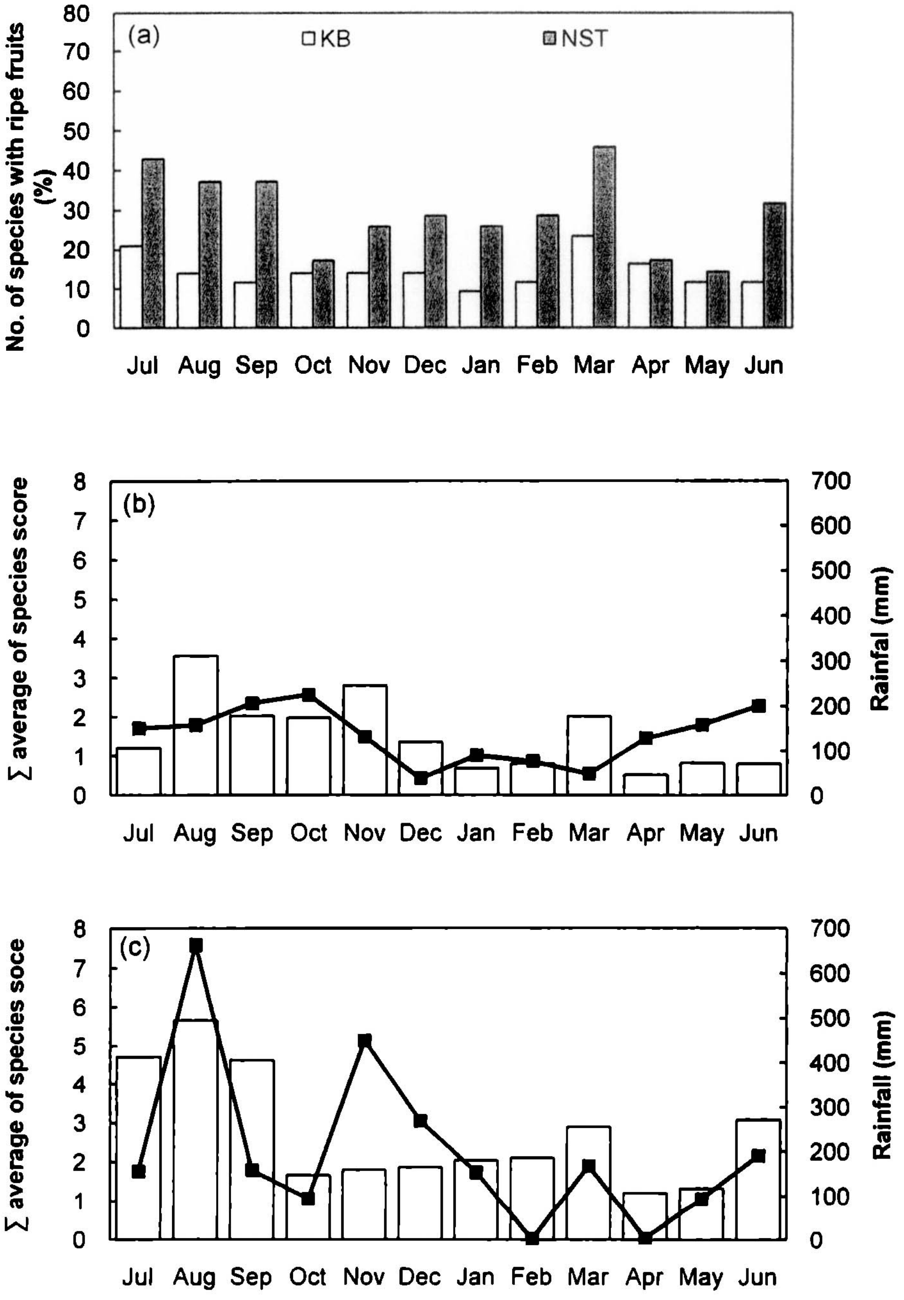

Figure 3.3 Observed patterns of community fruit ripening; (a) no. of species with ripe fruits, and sum average of species score at (b) KB = Krabi and (c) NST = Nakhon Si Thammarat

a. Flowering

Only species that flowered during the one year's observation were further processed with the calculation on the indices. Data on flowering for individual species at KB and NST are presented in Table 3.2 and 3.3 respectively. Flowering episodes commonly lasted less than 1 month in KB (68%) but 1-2 months in NST (48%). None of studied species had prolonged flowering episodes lasting up to five months in KB whereas 5 species did in NST (*V. pinnata*, *C. excavate*, *C. castanocarpus*, *C. brachiata* and *K. andamanica*).

As mentioned earlier, an annual fruiting pattern was the most common at KB and subannual fruiting was more common at NST. Therefore, the mean frequency of flowering at the species level was generally less than 1.00 in KB and more than 1.00 in NST. Nevertheless, there were 9 and 2 species with no flowering at KB and NST respectively during the observation period.

The intensity with which individuals produced flowers was generally moderate (almost 60%) at both sites, only few species attaining maximum intensity when they flowered; 3 species at KB (*D. venosa*, *E. stipularis* and *M. elliptica*) and only one species at NST (*P. pterocarpum*). Similarly, not many species consistently produced flowers in very small quantities per tree (less than 25%); 4 species at KB (*S. indica*, *E. papillosa*, *B. ramiflora* and *E. bengalensis*) and 3 species at NST (*D. kerrii*, *C. iners* and *D. alatus*).

More than half of the individuals of most studied species flowered each year, and the mean prevalence percentages were higher than 50% at both sites. However, the prevalence of flowering was quite low for some species, less than 25%, including 4 species at KB (*C. atropurpurea*, *D. obovata*, *D. kerrii* and *E. syzygioides*) and one species at NST (*B. ramiflora*).

Table 3.2 Flowering phenology in Krabi

Species	Duration (months)	Frequency (per year)	Intensity (%)	Prevalence (%)
Alstonia macrophylla	1.44	1.14	77.00	85.71
Antidesma ghaesembilla	0.73	1.60	60.00	100.00
Antidesma leucopodium	0.68	0.75	56.25	50.00
Artocarpus dadah	0.86	0.75	66.75	75.00
Baccaurea ramiflora	0.57	0.50	25.00	50.00
Callerya atropurpurea	0.66	0.33	43.75	16.67
Canthium glabrum	0.57	0.50	37.50	50.00
Carallia brachiata	1.58	0.50	70.75	50.00
Castanopsis schefferiana	0.89	1.17	62.50	66.67
Chaetocarpus castanocarpus	0.95	0.83	90.00	83.33
Clausena excavata	1.29	0.67	43.75	66.67
Dillenia obovata	0.61	0.17	50.00	16.67
Dipterocarpus kerrii	0.61	0.17	62.50	16.67
Diospyros venosa	1.25	0.40	100.00	33.33
Elaeocarpus stipularis	1.71	0.80	100.00	80.00
Eriobotrya bengalensis	0.70	0.50	25.00	50.00
Eugenia grandis	0.61	0.33	87.50	33.33
Eugenia papillosa	0.57	1.00	22.50	100.00
Eugenia syzygioides	0.79	0.20	87.50	20.00
Garcinia hombroniana	1.09	0.67	53.25	66.67
Garcinia merguensis	0.68	0.25	75.00	25.00
Horsfieldia irya	0.72	1.00	31.25	66.67
Lepisanthes rubiginosa	1.89	0.25	50.00	25.00
Litsea grandis	3.05	0.40	93.75	40.00
Madhuca malaccensis	0.86	0.60	33.25	60.00
Microcos paniculata	1.54	1.50	76.00	100.00
Morinda elliptica	2.48	1.00	100.00	100.00
Peltophorum pterocarpum	0.95	2.17	65.25	100.00
Radermachera pinnata	0.77	0.50	31.25	50.00
Sandoricum koetjape	0.68	0.50	56.25	50.00

Table 3.2 (Continued)

Species	Duration (months)	Frequency (per year)	Intensity (%)	Prevalence (%)
Saraca indica	0.61	0.25	12.50	25.00
Schima wallichii	0.69	0.71	55.00	71.43
Scolopia spinosa	0.68	0.33	37.50	33.33
Vitex pinnata	3.44	1.88	57.50	87.50

Table 3.3 Flowering phenology in Nakhon Si Thammarat

Species	Duration (months)	Frequency (per year)	Intensity (%)	Prevalence (%)
Antidesma ghaesembilla	1.80	1.67	41.75	100.00
Baccaurea ramiflora	1.20	0.33	43.75	16.67
Bhesa robusta	2.02	1.67	56.25	83.33
Callerya atropurpurea	3.34	1.44	52.75	100.00
Canthium glabrum	1.95	1.29	70.50	100.00
Carallia brachiata	8.80	1.67	79.75	100.00
Chaetocarpus castanocarpus	6.21	1.50	75.00	100.00
Cinnamomum iners	0.80	0.50	16.75	50.00
Clausena excavate	5.57	2.00	63.75	100.00
Dillenia parviflora	1.07	1.80	60.00	100.00
Diospyros oblonga	0.74	1.67	45.00	83.33
Diospyros pilosanthera	1.40	1.71	65.25	100.00
Diospyros venosa	3.04	1.17	52.00	66.67
Dipterocarpus kerrii	0.77	0.33	12.50	33.33
Dipterocarpus alatus	1.03	0.80	22.00	80.0
Elaeocarpus griffithii	3.43	2.00	72.00	100.00
Elaeocarpus stipularis	1.21	0.80	84.50	80.00
Eugenia borneense	3.39	2.00	75.00	100.00
Eugenia grandis	0.83	0.50	41.75	50.00
Garcinia cowa	0.94	0.67	59.50	66.67
Intsia palembanica	0.73	0.57	35.50	42.86
Knema andamanica	10.22	1.00	75.00	100.00
Lagerstroemia balansae	3.47	1.00	75.00	100.0
Lepisanthes rubiginosa	1.16	1.00	45.75	100.00
Litsea grandis	1.67	0.67	72.00	66.67
Mallotus paniculatus	2.63	2.00	89.50	100.00
Microcos paniculata	2.66	2.00	54.25	100.00
Morinda elliptica	3.92	2.00	79.25	100.00
Peltophorum pterocarpum	1.75	1.00	100.00	100.00
Sandoricum koetjape	1.10	1.00	87.50	100.00

Table 3.3 (Continued)

Species	Duration (months)	Frequency (per year)	Intensity (%)	Prevalence (%)
Streblus asper	2.14	1.80	62.50	100.00
Vitex pinnata	5.13	2.00	65.75	100.00
Vatica pauciflora	1.59	2.20	41.75	100.00

b. Fruiting

Data on fruiting phenology for each species observed at KB and NST were presented in Table 3.4 and 3.5 respectively. Fruiting episodes varied from less than 1 month to more than 8 months (only *C. castanocarpus* at NST). On average, fruits remained on the tree almost twice as long as flowers at KB (mean of all species = 1.96 months compared with 1.09 months for flowers) but remained at almost similar time period at NST (mean of all species = 2.98 months compared with 2.65 months for flowers).

Fruiting frequency, intensity, and prevalence values were likely depended on the flowering values. The fruit set rate was quite similar at both site (55 and 63% at KB and NST respectively) except 4 species had failed to develop into fruits at KB (*C. glabrum*, *E. grandis*, *S. indica* and *S. spinosa*). The fruit set was rarely 100% but *D. venosa* and *L. balansae* were achieved this success at KB and NST respectively.

Table 3.4 Fruiting phenology in Krabi

Species	Duration (months)	Frequency (per year)	Intensity (%)	Prevalence (%)	Fruit set (%)
Alstonia macrophylla	4.22	1.14	68.75	85.71	85.52
Antidesma ghaesembilla	1.81	1.60	41.25	100.00	65.00
Antidesma leucopodium	1.03	0.75	37.50	50.00	62.50
Artocarpus dadah	1.77	0.50	37.50	50.00	50.00
Baccaurea ramiflora	0.57	0.50	12.50	50.00	61.11
Callerya atropurpurea	1.38	0.33	18.75	16.67	45.83
Canthium glabrum	-		-		0
Carallia brachiata	3.13	0.33	100.00	33.33	66.67
Castanopsis schefferiana	1.46	1.17	34.50	66.67	45.00
Chaetocarpus castanocarpus	4.14	0.83	77.50	83.33	85.00
Clausena excavata	0.57	0.33	12.50	33.33	50.00
Dillenia obovata	2.00	0.17	25.00	16.67	50.00
Dipterocarpus kerrii	0.79	0.17	50.00	16.67	80.00
Diospyros venosa	4.82	0.40	100.00	33.33	100.00
Elaeocarpus stipularis	4.29	0.80	75.00	80.00	75.00
Eriobotrya bengalensis	0.79	0.33	18.75	33.33	38.89
Eugenia grandis		-		-	0
Eugenia papillosa	0.57	1.00	15.00	100.00	73.33
Eugenia syzygioides	1.22	0.20	75.00	20.00	85.71
Garcinia hombroniana	1.44	0.67	34.50	66.67	68.45
Garcinia merguensis	4.00	0.25	50.00	25.00	66.67
Horsfieldia irya	0.68	0.33	12.50	33.33	12.50
Lepisanthes rubiginosa	0.61	0.13	25.00	12.50	16.67
Litsea grandis	0.98	0.40	87.50	40.00	92.86
Madhuca malaccensis	1.38	0.40	18.75	40.00	30.00
Microcos paniculata	1.12	1.50	39.50	100.00	51.76
Morinda elliptica	3.42	1.00	100.00	100.00	95.83
Peltophorum pterocarpum	4.09	2.17	52.00	100.00	80.85
Radermachera pinnata	0.70	0.50	12.50	50.00	41.67
Sandoricum koetjape	1.59	0.50	43.75	50.00	67.86

Table 3.4 (Continued)

Species	Duration (months)	Frequency (per year)	Intensity (%)	Prevalence (%)	Fruit set (%)
Saraca indica	-	-	-	-	0
Schima wallichii	0.98	0.43	45.75	42.86	48.33
Scolopia spinosa	-		-	-	0
Vitex pinnata	3.32	1.75	39.50	43.26	87.50

Table 3.5 Fruiting phenology in Nakhon Si Thammarat

Species	Duration (months)	Frequency (per year)	Intensity (%)	Prevalence (%)	Fruit set (%)
Antidesma ghaesembilla	2.42	1.50	39.50	83.33	59.72
Baccaurea ramiflora	3.22	0.33	31.25	16.67	75.00
Bhesa robusta	4.42	1.67	46.25	83.33	81.67
Callerya atropurpurea	3.65	1.33	35.25	88.89	63.52
Canthium glabrum	3.39	1.29	51.75	100.00	66.17
Carallia brachiata	0.84	1.17	37.75	100.00	44.99
Chaetocarpus castanocarpus	8.77	1.50	62.50	100.00	83.33
Cinnamomum iners	0.82	0.17	25.00	16.67	33.33
Clausena excavate	5.63	2.00	52.50	100.00	87.50
Dillenia parviflora	1.58	1.80	43.75	100.00	68.55
Diospyros oblonga	1.38	1.33	30.00	83.33	61.00
Diospyros pilosanthera	1.96	1.00	25.00	57.14	29.76
Diospyros venosa	1.91	1.17	24.00	66.67	50.18
Dipterocarpus kerrii	0.82	0.33	25.00	33.33	62.50
Dipterocarpus alatus	2.32	0.80	12.50	80.00	45.83
Elaeocarpus griffithii	4.42	2.00	56.25	100.00	78.13
Elaeocarpus stipularis	2.39	0.80	37.50	80.00	40.48
Eugenia borneense	2.52	2.00	61.75	100.00	82.66
Eugenia grandis	1.39	0.50	12.50	50.00	34.44
Garcinia cowa	2.47	0.67	50.00	66.67	86.01
Intsia palembanica	1.76	0.43	16.75	42.86	44.44
Knema andamanica	1.64	1.00	25.00	100.00	33.33
Lagerstroemia balansae	6.07	1.00	75.00	100.00	100.00
Lepisanthes rubiginosa	0.77	0.33	43.75	33.33	23.33
Litsea grandis	0.83	0.50	16.75	50.00	23.36
Mallotus paniculatus	2.17	1.67	85.50	100.00	80.56
Microcos paniculata	4.19	2.00	40.75	100.00	76.75
Morinda elliptica	4.62	2.00	69.75	100.00	88.58
Peltophorum pterocarpum	5.51	1.00	91.75	100.00	91.67

Table 3.5 (Continued)

Species	Duration (months)	Frequency (per year)	Intensity (%)	Prevalence (%)	Fruit set (%)
Sandoricum koetjape	5.45	1.00	75.00	100.00	86.51
Streblus asper	2.29	1.80	53.75	100.00	78.57
Vitex pinnata	5.16	2.00	44.75	100.00	68.33
Vatica pauciflora	1.66	1.80	23.00	80.00	45.56

In general, about half of the tree species studies at KB and 80% at NST produced ripe fruits during observation period. Most species were ready to disperse ripe fruits in March, which was the beginning of dry season at NST but the late of dry season for KB. Species that bear ripe fruits, prior to the onset of rainy season, should be targeted as the potential candidates for direct seeding, since seed storage is not necessary for their use, and the seeds of many lowland tropical forest tree species are recalcitrant and cannot be stored. In this study 12 tree species at KB (April - May) (Figure 3.4) and 15 tree species at NST (August - September) (Figure 3.5) met this criterion. *V. pinnata* was the only species, which produced ripe fruits almost all year round in southern Thailand and it might therefore also be suitable for testing for direct seeding.

Species	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
Alstonia macrophylla		X		X	X							
Antidesma ghaesembilla			X	X	X							
Antidesma leucopodium											X	X
Artocarpus dadah			X						**X**			
Baccaurea ramiflora	X											
Carallia brachiata							X	X	**X**			
Castanopsis schefferiana	X	X										
Chaetocarpus castanocarpus							X	X	**X**	**X**		
Dillenia obovata										**X**	X	
Diospyros venosa								X	**X**			
Elaeocarpus stipularis				X	X	X						
Eugenia papillosa	X											
Eugenia syzygioides									**X**			
Garcinia hombroniana									**X**	**X**		
Garcinia merguensis						X						
Lepisanthes rubiginosa									**X**	**X**		
Litsea grandis										**X**		
Microcos paniculata				X	X	X						
Morinda elliptica	X										X	X
Peltophorum pterocarpum	X	X	X	X	X	X						X
Sandoricum koetjape	X	X								**X**	X	
Schima wallichii	X								**X**			
Vitex pinnata	X	X	X	X	X	X	X	X	**X**	**X**	X	X

Figure 3.4 List of species with ripe fruit fruits monthly in Krabi; bold X represents target species for direct seeding

Species	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
Antidesma ghaesembilla	X	**X**	**X**		X	X			X		X	X
Baccaurea ramiflora	X	**X**	**X**									
Bhesa robusta	X	**X**	**X**		X	X			X		X	X
Callerya atropurpurea	X	**X**				X	X		X			
Canthium glabrum			**X**	X		X		X	X			
Carallia brachiata									X			
Chaetocarpus castanocarpus	X			X	X	X	X	X	X	X		X
Cinnamomum iners									X			
Clausena excavate	X	**X**	**X**	X	X	X	X		X	X	X	X
Dillenia parviflora											X	
Diospyros oblonga												X
Diospyros pilosanthera		**X**	**X**	X	X			X				
Dipterocarpus kerrii									X			
Elaeocarpus griffithii							X	X	X			
Eugenia borneense	X	**X**	**X**		X	X	X	X	X	X	X	X
Garcinia cowa	X	**X**	**X**									
Intsia palembanica	X	**X**	**X**						X			
Lagerstroemia balansae							X	X	X			
Lepisanthes rubiginosa								X		X		
Litsea grandis							X					
Mallotus paniculatus								X				
Microcos paniculata	X		**X**	X	X	X	X	X	X			X
Morinda elliptica	X				X	X						
Peltophorum pterocarpum	X	**X**	**X**									
Sandoricum koetjape	X	**X**	**X**									X
Streblus asper		**X**							X	X		X
Vitex pinnata	X	**X**	**X**	X	X	X	X	X	X	X		X

Figure 3.5 List of species with ripe fruit fruits monthly in Nakhon Si Thammarat; bold X represents target species for direct seeding

3.3.2 Leafing phenology

Annual patterns of leaf abscission showed flat curve during the rainy season (almost <5% at all months) but moderately change in the dry season. The highest peak was found during March to April, similar at both sites (Figure 3.6).

Similarly, leaf flushing was high during the dry season. There was a marked peak of leaf production at about one month later to leaf shedding at NST (April - May) while a flat and long peak was observed at KB during early dry to early rainy season (November - June) (Figure 3.7).

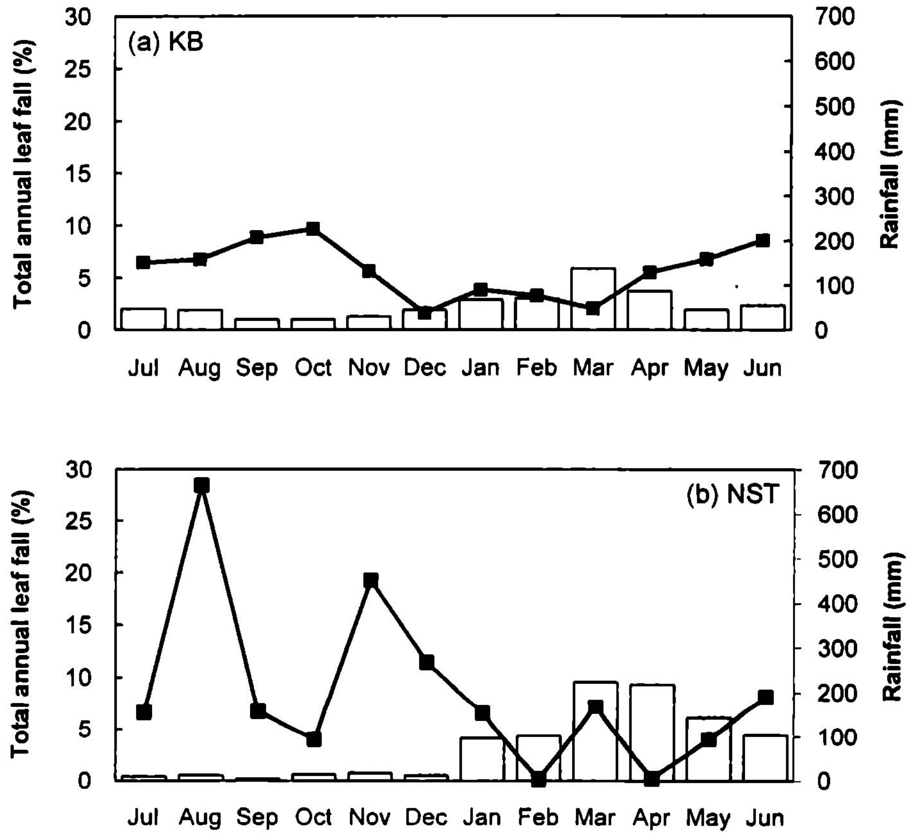

Figure 3.6 Observed patterns of community leaf fall; (a) KB = Krabi and (b) NST = Nakhon Si Thammarat

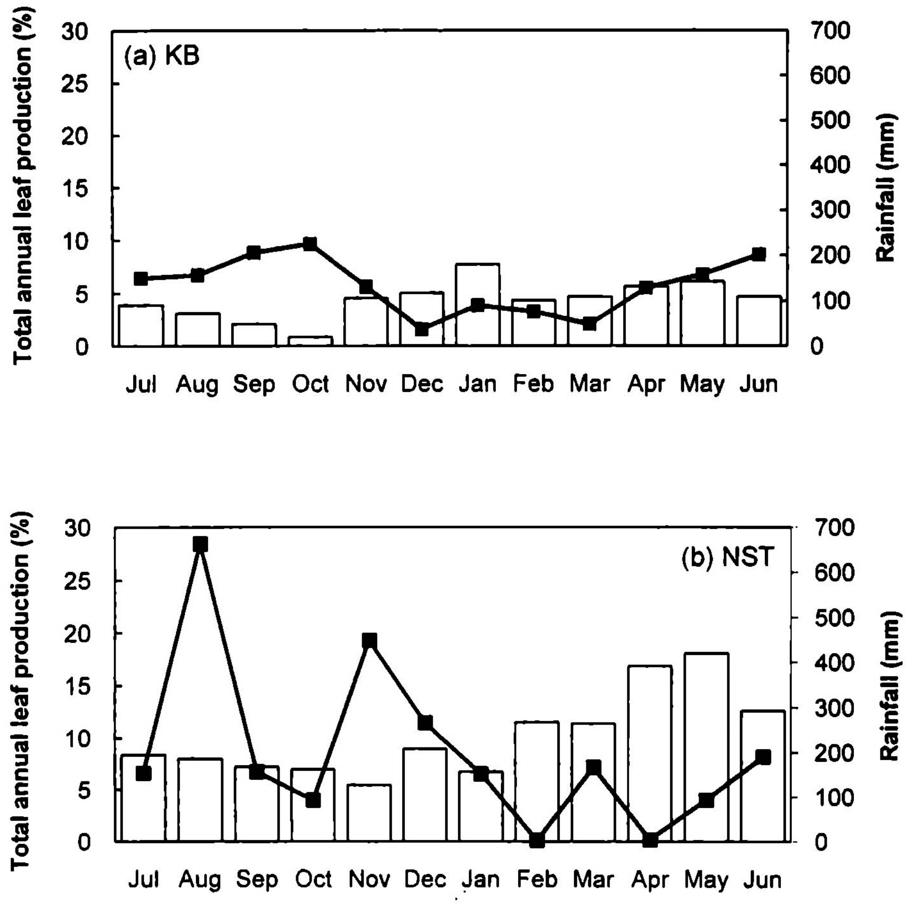

Figure 3.7 Observed patterns of community leaf production; (a) KB = Krabi and (b) NST = Nakhon Si Thammarat

3.3.3 Phenological patterns in relation to different precipitation regimes

Reproductive success was achieved by 10 out of 22 species that were common to both the east (NST) and the west coast (KB) of southern Thailand during the observation (July 2009 to June 2010). Four species did not flower (*C. iners*, *E. borneense*, *G. cowa* and *I. palembanica*), 3 species (*A. angustiloba*, *B. ramiflora* and *C. glabrum*) flowered but failed to set fruit , and another 3 species (*C. atropurpurea*, *C. excavata* and *D. kerrii*) lost their fruits before ripening at KB while all those species bore fruit to a ripe condition at NST. All species flowered at NST except *D. venosa* and *E. stipularis* that could not reach the ripe stage.

To emphasize that the seasonal patterns are different between the east and the west coast of southern Thailand, particularly the dry period during the year, from the long climatic record (1989 - 2008), the dry season lasted from November to April at KB while it lasted from March to September at NST with almost two times higher of monthly precipitation at NST than KB.

In spite of the differences in dry season period and intensity, flowering of five species followed the same temporal pattern at both study sites. Four species (*A. ghaesembilla*, *L. rubiginosa*, *M. paniculata* and *P. pterocarpum*) flowered in the same month (Figure 3.8-3.11) and *V. pinnata* flowered and bored fruits all year round at both sites (Figure 3.12).

In contrast, 3 species (*L. grandis*, *M. elliptica* and *S. koetjape*) flowered later at NST than at KB (Figure 3.13-3.15), the time interval was slightly varied within few months among species.

Different flowering patterns between the two sites were observed for 2 species (*C. brachiata* and *C. castanocarpus*). *C. brachiata* flowered continually and bore fruits twice a year at NST. At KB 2 peaks of flowering (in late dry and rainy season) were observed with fruiting mainly occurring in between (Figure 3.16). Three peaks of flowing of *C. castanopsis* (September, November and January) were observed at NST with continual fruiting throughout the year. In contrast, only one peak of flowering was observed at KB with subsequently 4 months of fruiting (Figure 3.17).

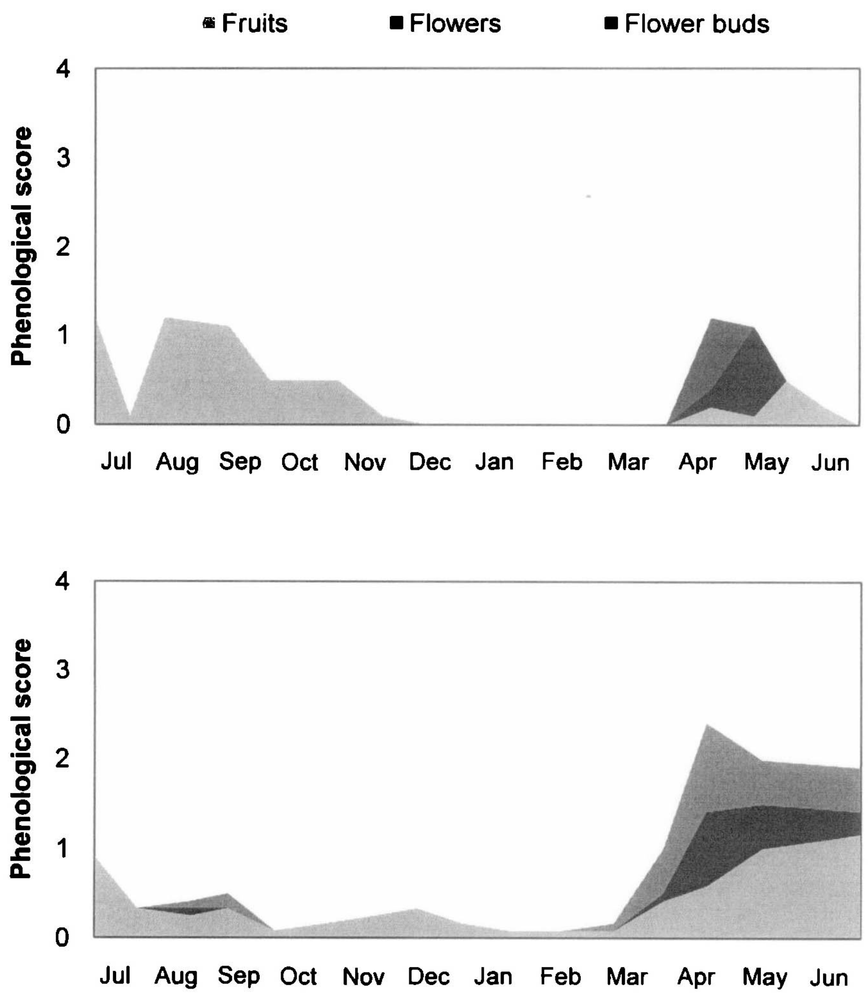

Figure 3.8 Phenological patterns of reproductive parts of *A. ghaesembilla* in (a) Krabi and (b) Nakhon Si Thammarat

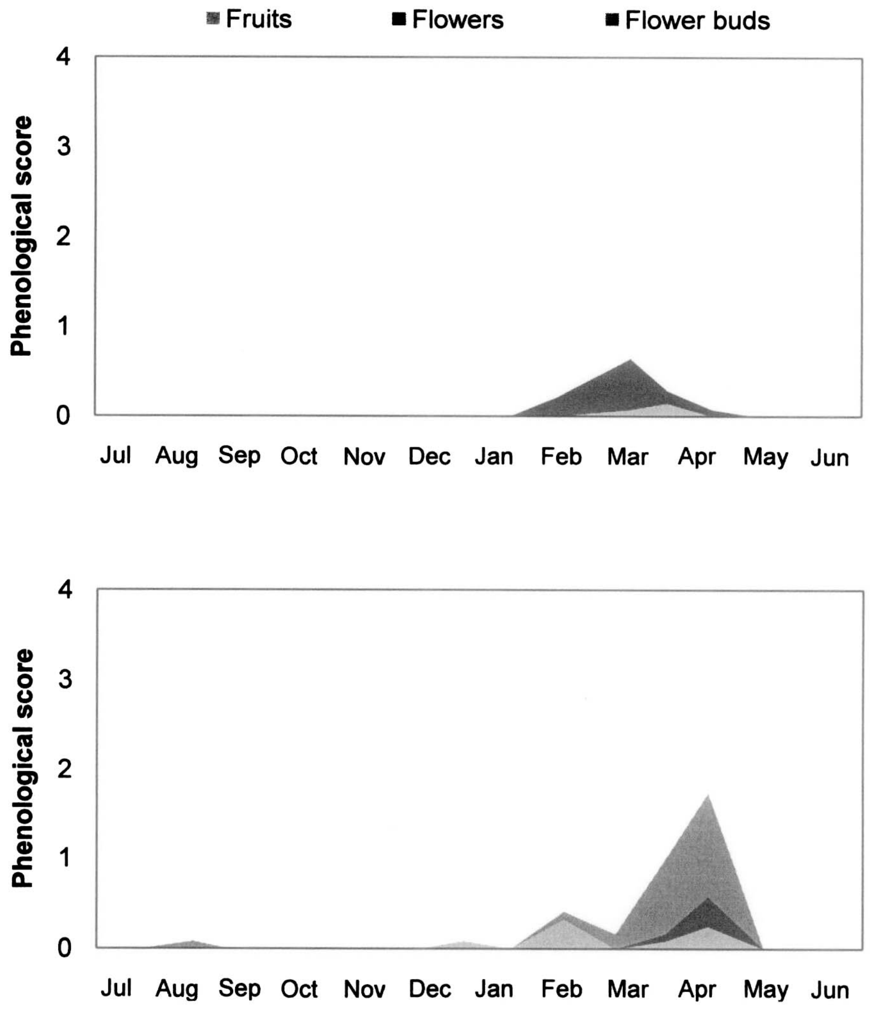

Figure 3.9 Phenological patterns of reproductive parts of *L. rubiginosa* in (a) Krabi and (b) Nakhon Si Thammarat

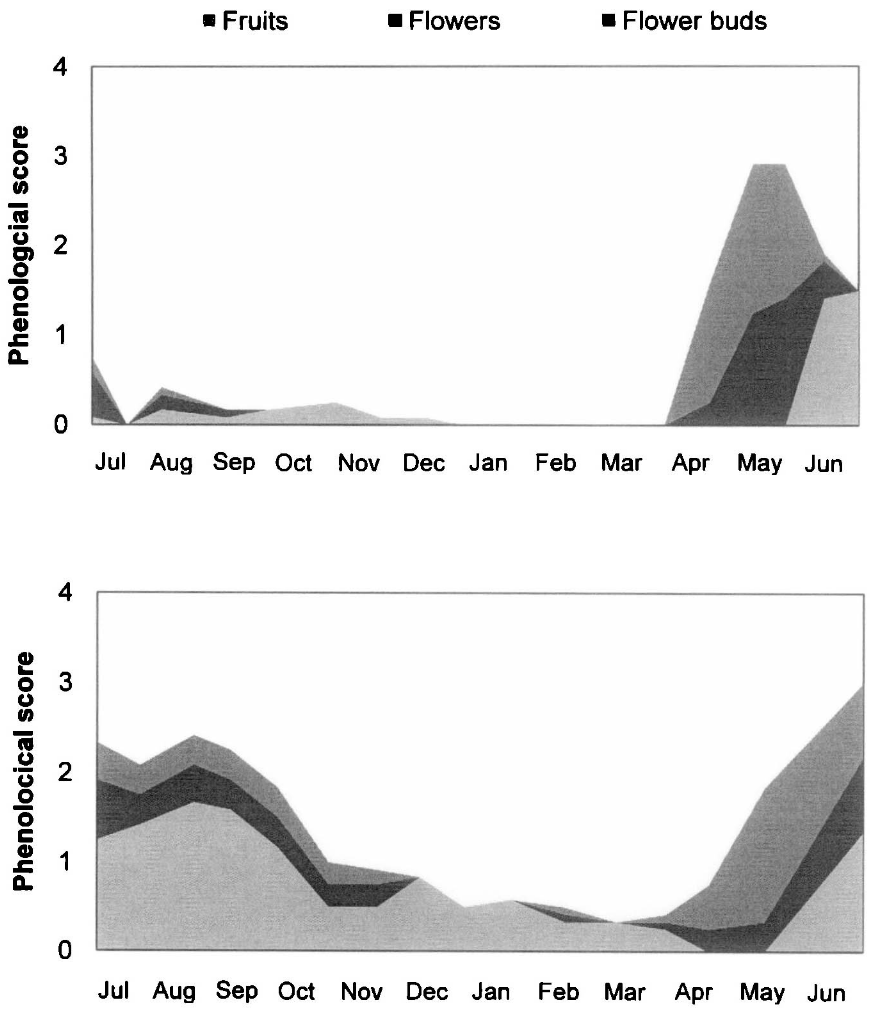

Figure 3.10 Phenological patterns of reproductive parts of *M. paniculata* in (a) Krabi and (b) Nakhon Si Thammarat

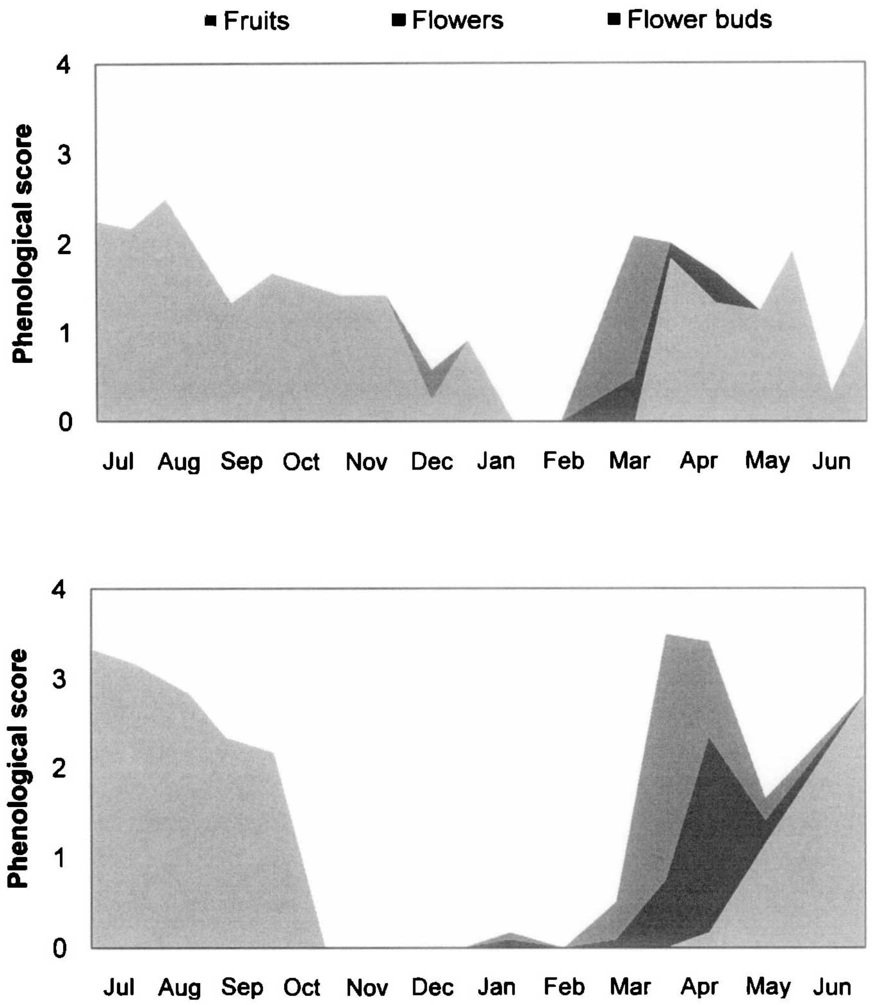

Figure 3.11 Phenological patterns of reproductive parts of *P. pterocarpum* in (a) Krabi and (b) Nakhon Si Thammarat

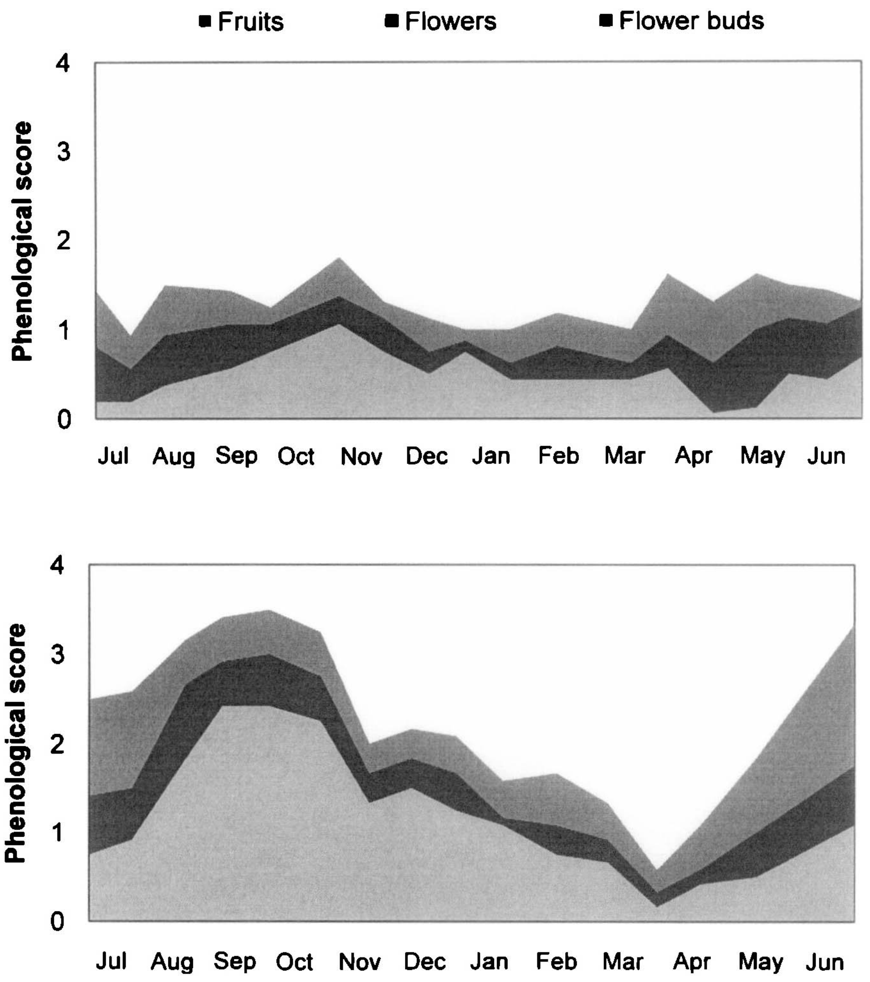

Figure 3.12 Phenological patterns of reproductive parts of *V. pinnata* in (a) Krabi and (b) Nakhon Si Thammarat

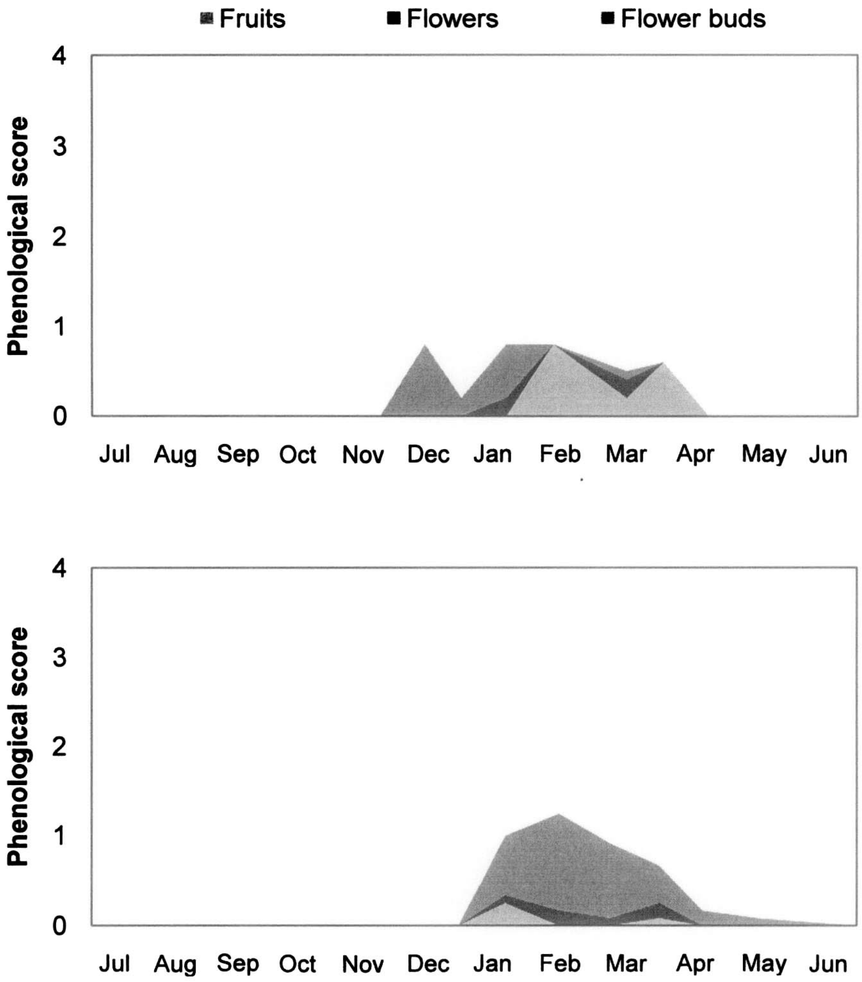

Figure 3.13 Phenological patterns of and reproductive parts of *L. grandis* in (a) Krabi and (b) Nakhon Si Thammarat

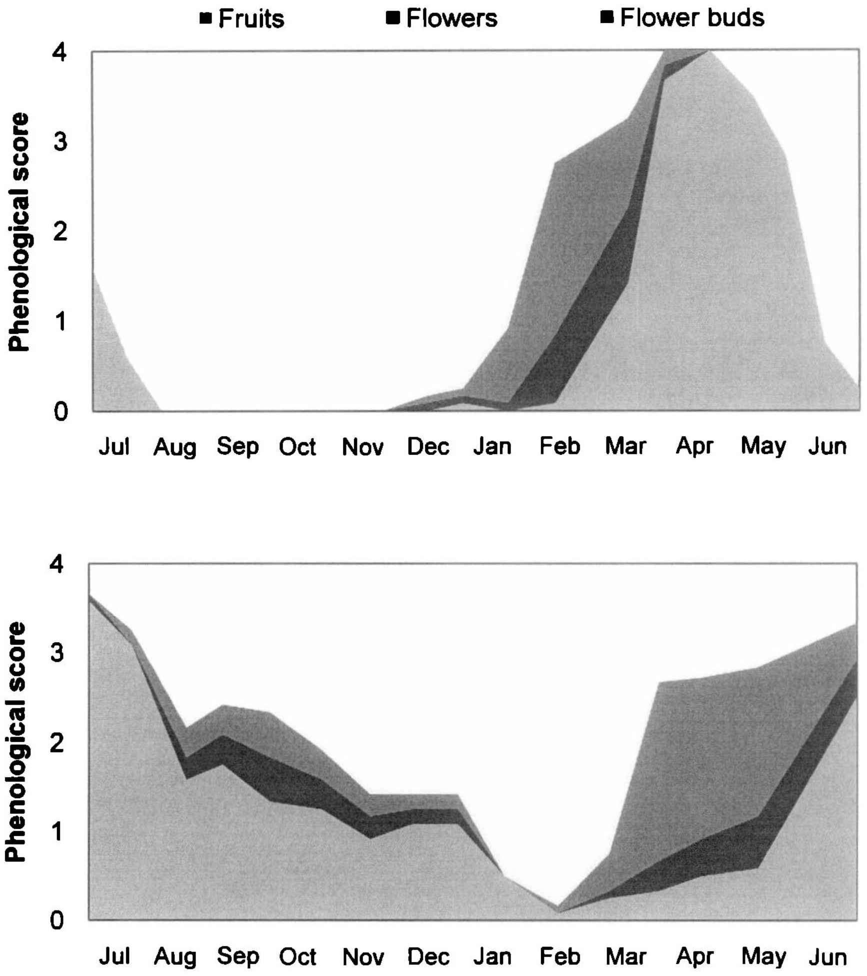

Figure 3.14 Phenological patterns of reproductive parts of *M. elliptica* in (a) Krabi and (b) Nakhon Si Thammarat

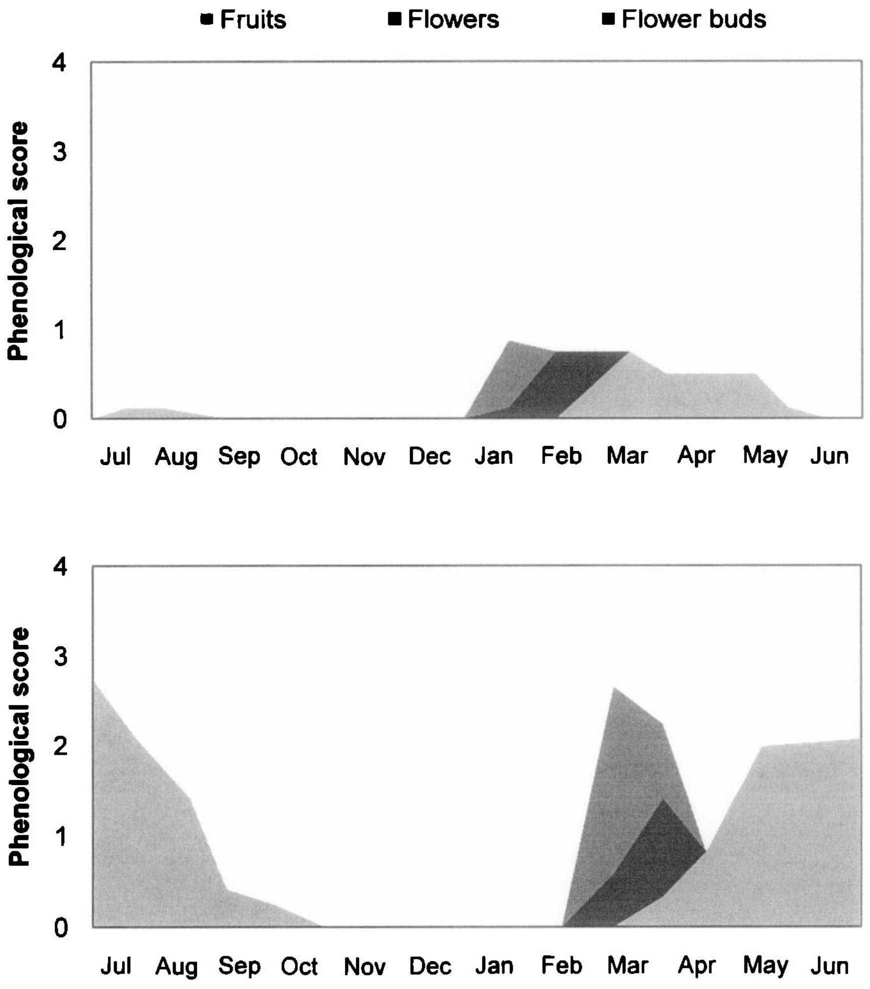

Figure 3.15 Phenological patterns of reproductive parts of *S. koetjape* in (a) Krabi and (b) Nakhon Si Thammarat

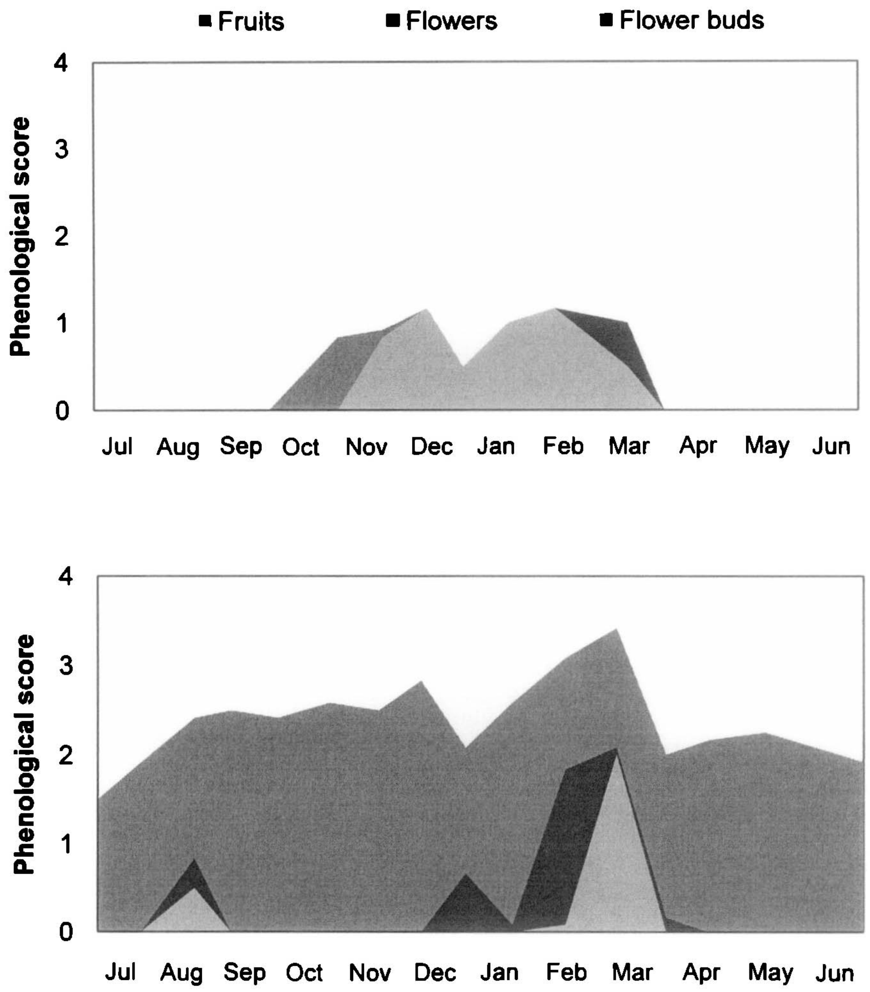

Figure 3.16 Phenological patterns of reproductive parts of *C. brachiata* in (a) Krabi and (b) Nakhon Si Thammarat

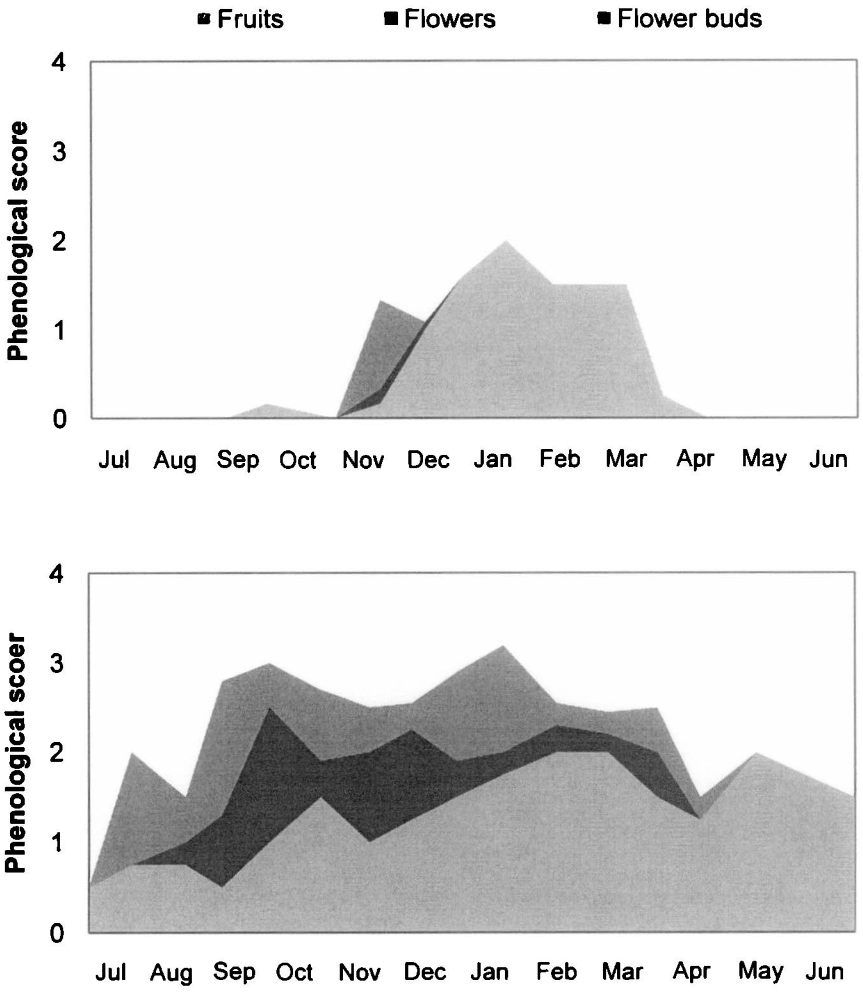

Figure 3.17 Phenological patterns of reproductive parts of *C. castanocarpus* (a) Krabi and (b) Nakhon Si Thammarat

3.4 Discussion

3.4.1 Reproductive phenology

Based on frequency as the criterion with priority (Newstrom et al., 1994), the flowering pattern differed between east and west coast of southern Thailand. Sub-annual flowering, more than once a year, was dominant at NST, while annual flowering was more common at KB, accounting for about half of the total species in each site. This is related to the mean frequency of flowering in both sites; less than 1.00 in KB and more than 1.00 in NST. Due to time limitation (only 1 year observation), this study failed to explain the species with no flowering whether they are supra-annual flowering type, which is the predominant in a large portion of Asian tropical forests (Sakai, 2001), or due to the immaturity of the sampled trees or because they were growing in a suboptimal habitat (Elliott et al., 1994).

These flowering patterns were similar to those observed in neotropical forests where that higher proportion of annual flowering species occurred with stronger seasonality (Sakai, 2001). Moreover, a small proportion of the continual flowering type was observed at both sites, emphasized the similarity to the study in neotropical forest at La Selva, Costa Rica (Newstrom et al., 1994) while none of this flowering pattern was found in Lambir, Malaysia (Newstrom et al., 1994; Sakai, 2000, 2001).

The timing of flowering in lowland forest in southern Thailand was similar to that of seasonally dry tropical forests where flowering periodicity becomes more distinct with declining annual precipitation and increasing severity of the dry season (Borchert et al., 2004). In the lowland forest in southern Thailand, there were one peak of flowering in the middle to late dry season (both KB and NST) and another peak during the first rains of the year (only at NST). In the seasonally dry tropical forests, flowering is often concentrated in the transition from the late dry to the early wet season (Murali & Sukumar, 1994), similar to the tropical dry evergreen forests that reproductive activity are concentrated during dry season (Nayak and Davidar, 2010). This may be caused by enhancement of germination and seedling survival by adjusting fruiting to precede the beginning of the rainy season (Van Schaik et al., 1993). However, an additional peak of flowering during the first heavy rains at NST begs the question of how the observed difference in flowering periodicity might be related to climatic differences. Recent analyses of the proximate controls of flowering in individual tropical dry forest species have shown that flowering periods are strongly determined by the timing of vegetative phenology and thus depend at least indirectly on environmental periodicity (Borchert, 1983; Rivera & Borchert, 2001; Rivera et al., 2002). The observed flowering patterns in this study could be classified into two types following the study of Borchert (2004), the first type was winter species which flowered during mid dry season and another one was early summer species flowered soon after the first rains, those two flowering types were mentioned to be triggered by drought-induced leaf shedding and first heavy rain respectively. Longer term observations in a broader range of forest types is necessary to confirm the concept in this region.

From this study, 4 species at KB and 3 species at NST produced flowers in very small quantities (less than 25%) might be because unsuitable environments for reproduction (Elliot et al., 1994) or they might share flowering events with general flowering which only a few flowers can be seen in non-GF periods (Sakai, 2000). For example, two dipterocarp species in NST which is known to flower during GF or mass flowering in lowland dipterocarp forests in this region (Ashton et al., 1988; Fenner, 1998).

At NST, where two peaks of flowering were observed during the first heavy rain and dry season, two peaks of fruit ripening were also observed but with a difference in terms of total quantity. The species that flowered during the dry season produced dry fruits which matured in the dry season (Justiniano & Fredericksen, 2000) and most seeds remain dormant until the beginning of the rainy season, when they suddenly germinate (Garwood, 1983). However, another peak was in the middle of rainy season which corresponded with maturation of fleshy fruits occur (Singh & Singh, 1992). Moreover, unsuccessful pollination might have caused the low quantity of ripe fruits developed from species that flowered during dry season at NST. Similarly, two peaks of fruit ripening were also observed in KB, one near the end of dry season, which is common in seasonally dry tropical forests but another moderate peak was in the rainy season. Morphology and physiology of seeds should be further investigated for more understanding on seasonal seed maturation. On the other hand, the role of biotic interactions has long been controversial in shaping plant flowering (Elzinga et al., 2007) but they would not be discussed here.

Fruiting intensity depended to a large extent on the respective flowerings values. The species that could attain maximum intensity of flowers (100%) (*D. venosa*, *E. stipularis*, *M. elliptica* and *P. pterocarpum*) seemed to represent their suitability to the habitat, in terms of physical and biological factors, therefore they were successfully produced high quantity of fruits (>90% fruit set index). In contrast, some species failed to develop into fruits (*C. glabrum*, *E. grandis*, *S. indica* and *S. spinosa*) although they attained to moderate intensities of flowering (13-88%). At the level of the individual plant, inter-annual variation in pollination success influences fruit crop size in the tropical forests (Jordano & Schupp, 2000). For example, the study of Nayak and Davidar (2010) on pollination and breeding systems of woody plant species in tropical dry evergreen forests in India showed that self-incompatible species having low fruit set because of pollination failure. In addition, lacking of sufficient pollination modes due to degree of disturbance (Corlett, 2007; Ramírez, 2004) is possibly a major cause to low fruit set of the studied species.

3.4.2 Leafing phenology

Leafing phenology of tropical forests is distinct from other biomes with development tends to be continuous in aseasonal lowland tropical rain forests and becomes more episodic in response to increasing annual drought in tropical dry forests (Reich, 1995). Annual patterns of leaf drop showed slightly change during the rainy season similar to the patterns observed in rain forest in neotropical sites but markedly change in the dry season possibly due to soil moisture and tree water status constraints (Reich, 1995; Reich & Borchert, 1984). The modest peak in leaf senescence that occurs in rain forests do appear to be related to the early dry season (Frankie et al., 1974) and this pattern was found on the east coast at NST. A slightly different pattern was found on the west coast at KB, leaf shedding was gradually increased at the beginning of dry season and markedly increased by the end of dry season when the maximum temperature was highest in the year. Correspondingly, it had been reported that greatest leaf fall corresponded to the driest periods both in wet (La Selva) and dry forests (Comelco) in Costa Rica (Reich, 1995).

The production of new leaves in a tree requires sufficient carbon, water and nutrients, the availability of which is directly and indirectly influenced by intra- and interannual variations in environmental conditions (Williams & Bunyavejchewin, 2008). Leaf flushing was high during dry season in southern Thailand, similar to the study in a seasonal tropical forest in western Thailand (Williams & Bunyavejchewin, 2008). Van Schaik et al. (1993) proposed that the timing correlated with the peaks in annual irradiance. The study in neotropical forests (Borchert et al., 2004) reported that most trees form new leaves during relatively short periods, which vary among species of different functional types. In addition, flushing may be induced by the first heavy rains of the wet season, by leaf shedding during the dry season or by increasing photoperiod after the spring equinox (Borchert & Rivera, 2001; Rivera et al., 2002). Observed species leafed soon after partial leaf shedding in the early dry season at NST, while the flat and long peak was observed at KB, start from the beginning of the dry season till early rainy season. A recent study described vegetative phenology as parallel events of flowering period, for example, shoot and leaf expansion will occur with the flowering of summer species during summer rain, or winter species will flower during mid dry season after or during leaf exchange (Borchert et al., 2004).

These patterns were not correlated with rainfall, like the results from a large-scale irrigation experiment in Barro Colorado Island in Panama showed that irrigation had no effect on the timing of leaf flush for most species of canopy trees (Wright & Cornejo, 1990) because deep-rooting canopy trees possibly do not experience a water deficit, even in dry seasons (Steinberg et al., 1989). Furthermore, the study of Elliott et al. (2006) in the dry monsoon forests in Thailand showed that the species leafing during dry season relied on subsoil water reserve, which buffer trees against prolonged climatic drought. On the other hand, a major selective force in determining the timing of leafing may be the effects of herbivory (Fenner, 1998) and this is the supposed advantage of dry season flushing like the study of Murali and Sukumar (1994) showed that the late-flushing trees were damaged by the herbivorous insects which emerged with the rains.

3.4.3 Phenological patterns in relation to different precipitation regimes

Here I focused on 10 species that bore fruits at both KB and NST during the observation. From flowering patterns, it seems that two groups of species has can be distinguished; i) species which are genetically controlled (or which respond to day length) and ii) species which respond to environmental cues. Five species (*A. ghaesembilla*, *L. rubiginosa*, *M. paniculata*, *P. pterocarpum* and *V. pinnata*) that showed similar time of flowering in both observed sites, with different precipitation regimes, were possibly represented the first group. Flowering phenology may be constraint by its taxonomic affinities (Elzinga et al., 2007; Lobo et al., 2003; Sakai, 2001). Analyses of various floras confirm that this phylogenetic effect on flowering time is strong and its influence has been demonstrated in the floras of South West Australia, North America and Japan, and some plant families in Costa Rica and Mexico (Bell & Stephens, 1984; Kochmer & Handel, 1986; Lobo et al., 2003). In contrast, the flowering time of 3 species (*L. grandis*, *M. elliptica* and *S. koetjape*) was delayed a few months at NST, where the rainy season comes later for about 4 months. The time of flowering may be constrained by the timing of other phenophases such as growth, seed dispersal or seed germination (Johnson, 1993), or biotic interactions such as competition for pollinators, pre-dispersal seed predation (Lobo et al., 2003). Although the flowering time was different between two sites, however the fruiting time was likely the same. This might be implied that early flowering at KB was failed in terms of attracting pollinators, or fruit development period was shorter at NST.

Various abiotic and biotic factors can be selective agents for different flowering patterns of *C. brachiata* and *C. castanocarpus* between two sites. Plastic responses to the abiotic environment, limited precision of biological clocks and inconsistency are biotic interactions have generally been emphasized to explain phenology variation (Elzinga et al., 2007). Although, part of this variation is heritable, however there were many examples of phenological divergence between plant populations with the same species, each adapted to their local conditions (Antonovics, 2006; Mitchell-Olds & Schmitt, 2006; Quinn & Wetherington, 2002). Climate variation might modify selection on flowering phenology as growing seasons expand or contract (Franks et al., 2007), and this might modify biotic interactions if the phenology of interacting species shifts unevenly with climate (Elzinga et al., 2007).

In conclusion, the phenological patterns of lowland tropical species in southern Thailand had expressed the characters of both Neotropical forests and lowland forest in Southeast Asia. Different precipitation regimes between east and west coast of the peninsular had not influenced markedly on the reproductive phenology of observed species. Only *C. brachiata* and *C. castanocarpus* displayed obviously different patterns and this might be constrained by the biotic interactions which would not been covered by this study. A total of 12 and 15 species were targeted for seed collection for direct seeding, since they bored ripe fruits at the suitable time at KB and NST respectively. Other species could be further added to the list of candidates if future study can determine their storability. Long-term monitoring combined with physiology and phylogeny studies should be addressed to increase understanding of the role of biotic interactions that shaping plant phenology, particularly how these events may adapt trees to new climatic conditions.

Chapter 4

Seed characteristics and the early establishment of direct seeding

4.1 Introduction

Growing concerns over global biodiversity loss and climate change have generated a recent surge in interest in the potential to restore tropical forest ecosystems, both for wildlife conservation and carbon storage. Most forest restoration techniques involve tree planting, which is both expensive and time consuming, since growing trees to a plantable size in nurseries takes at least 1 year and is labour-intensive. Direct seeding (sowing forest tree seeds directly into deforested areas) could drastically reduce the costs of forest restoration (since nursery costs are eliminated), provided that it can be implemented effectively. However, few accounts of successful direct seeding to restore wet tropical forests have been reported and the method is often regarded as unreliable, due to many factors that limit germination and seedling establishment, such as lack of favourable micro-sites for germination (De Steven, 1991), seed predation (Hau, 1997), weed competition and unsuitable seed types (Doust et al., 2008).

Species choice is critical to the success of direct seeding. Tropical forests are home to many thousands of tree species. Collecting seeds of them all and testing them for germination and seedling establishment in deforested areas would be very time consuming. Therefore, this study explores the concept that success of direct seeding can be predicted from those seed traits that are already know to affect seed germination, dormancy and early seedling establishment, such as seed size, seed coat thickness, shape and moisture content.

Of these traits, seed size has been most explored. Large seeds carry with them greater food reserves giving very young seedlings a greater chance of survival, but the effects of seed size on success of direct seeding appears to be variable. For example, in Australia, Doust et al. (2006) showed that, for buried seeds, large ones had higher germination and seedling growth rates than small or intermediate sized seeds. Within species, larger seeds are recommended for use in afforestation programs, because they have higher germination per cent, both in the laboratory and in the field (Manga & Sen, 1995). Studies, suggesting that direct seeding is a promising restoration strategy for larger-seeded tree species, include those of Carmago et al. (2002), Doust et al. (2006) and Hardwick (1999), although the results vary among habitats. Despite this evidence, small-seeded pioneer species have more commonly been used to restore forest ecosystems, because they occur naturally at the early stages of succession (Balandier et al., 2009; Engel & Parrotta, 2001; Garcia-Orth & Martínez-Ramos, 2008; Sun et al., 1995). On the other hand, successful results have been achieved with some species that have moist, intermediate-sized seeds (Tunjai, 2005).

Large seeds, with thick seed coats, are less susceptible to predation (Hau, 1997; Nepstad et al., 1996), but thick seed coats can delay germination (Tunjai, 2005). For example, legumes are often excellent candidate species for direct seeding, especially due to their nitrogen fixing capabilities (Engel & Parrotta, 2001), but pre-sowing seed treatments are often necessary to reduce dormancy resulting from their hard seed coats (Cervantes et al., 1996). Seeds with thin seed coats can be more easily penetrated by water, which can trigger rapid germination (Bewley & Black, 1985). However, Badek et al. (2006) showed no relationship between seed coat thickness and seed germination percentage.

Apart from seed size, few studies from the humid tropics have attempted to identify other seed characteristics that could potentially be used to predict which tree species could be used successfully for direct seeding (Doust et al., 2008; Hooper et al., 2002; Knowles & Parrotta, 1995). Seed shape is also functionally important (Campbell et al., 1999). In combination with seed mass, seed shape appears to affect the probability of seed predation, persistence in the seed bank, dispersal ability, seed production, and establishment success (Liu et al., 2007). Round seeds could penetrate easily into the soil, persist longer before germination and consequently they are often dominant in the seed bank (Yu, et al., 2007). In contrast, many small-, elongated- or conically-shaped seeds germinate immediately after collection (Grime et al., 1981) because shorter distances between the embryo and seed surface reduce the barrier to moisture and oxygen penetration into the embryo. Moreover, round, large seeds present handling difficulties to seed predators (Cole et al., 2011).

Seed moisture content is major factor affecting seed quality and longevity. Moisture content and longevity are negatively correlated, except at very low moisture levels (Ellis et al., 1988). Moist seeds usually germinate rapidly after sowing in open areas, which is a useful characteristic for candidate species of direct seeding (Tunjai, 2005). However seed moisture content was not correlated with any of the germination variables in the study in Panama (Sautu et al., 2006).

Since these various seed traits interact with each other, a multivariate approach is needed to determine how seed structure as a whole contributes to success of direct seeding. Thus, the objectives of the present study were i) to determine the effects of seed traits (size, shape, seed coat thickness and moisture content) on dormancy, germination and seedling establishment in the harsh conditions prevalent in deforested sites, in order to develop a system for species selection for direct seeding on degraded areas in southern Thailand, and ii) to explain the associations between seed size and other life-history attributes. This study therefore tested the hypothesis that easily-measured seed traits can be used to predict which tree species can be successfully established by direct seeding.

4.2 Material and methods

4.2.1 Experimental design

Seeds of 19 indigenous lowland evergreen forest tree species were collected, at most, two months prior to sowing at each study site. Most seeds were collected from the ground and stored in the open containers at room temperature (Table 4.1). Seeds of only 4 species were stored in the refrigerator at 10°C, to extend their viability until sowing time (Table 4.1). Seeds were sown only near the sites where they were collected.

Direct seeding experiments were established in 2009 at the beginning of the wet seasons at both sites i.e. May at KB and September at NST. Weeds were cleared by tractor and four replicates of 40 seeds of each species (totally 160 seeds per species) were sown, with 11 species tested at KB and 9 species at NST (Table 4.1) in May and September respectively. Individual seeds spaced about 60 cm apart. Seeds were buried to an approximate depth of 3-45 mm depending on seed size, since reports show that burying results in higher establishment rates (Doust et al., 2006). No protective measures were put in place to prevent seed predation and seedling predation. Therefore, seeds counted as not germinated also included those removed by seed predators.

The seed traits tested in this study were size, shape, coat thickness and moisture content, since previous studies showed that these traits are likely to affect germination and dormancy and therefore contribute significantly towards seedling establishment (Bewley & Black, 1985; Cervantes et al., 1996; Doust et al. 2006; Grime et al., 1981; Liu et al. 2007; Tunjai, 2005; Yu et al., 2007).

Seeds were classified according to their mean dry mass as small (<0.01-0.099 g), intermediate (0.1-4.99 g) or large (>5 g) (Doust et al., 2006). Thirty seeds of each species were randomly selected and measured for length, width and thickness. The shape of diaspores was determined by the variance of three dimensions, i.e. length, width and height following Thomson et al. (1993) and Moles et al. (2000). Seed shape (variance of three dimensions), grouped into three categories: round (<0.06), oval (0.06-0.09) and flat (>0.09). The seed coat thickness of thirty randomly selected seeds of each species was then measured at 3 or 4 points, depending on the seed shape, using a stereo microscope (Leica Application Suite LAS ES version 1.4.0). Seed coats were classified as thin (mean<0.01-0.099 mm), moderate (mean 0.1-0.49 mm) or thick (mean >0.5 mm). Moisture content was determined for four replicates of 10-15 seeds (approx 5 g before drying) placed in an oven for 17±1 hours at 103±3°C. The samples were then placed in a desiccator to cool for about 20 minutes before weighing. The moisture content was calculated using the ISTA formula (ISTA, 2006; Schmidt, 2007). Seed moisture contents were classified as low (mean 0-35%), medium (mean 36-70%) or high (mean 71-100%).

4.2.2 Data collection and statistical analysis

The components that contribute to direct seeding success include high germination rate (since small numbers of seeds would need to be sown); rapid germination (reduces the time available for seed predation and maximizes seedling growth period before dry season) and high seedling survival over the first year after germination. Germination was monitored weekly until 4 weeks had elapsed without any further seeds germinating, after a clear peak had occurred. Germination percentage and median length of dormancy (MLD) were calculated for each species. MLD was defined as the length of time between sowing and germination of half the seeds which eventually germinate (FORRU, 2008a) for each replicate. The numbers of surviving seedlings at both sites were recorded, one year after sowing, as the ultimately measure of direct seeding success. In addition, growth performance (height, root collar diameter and canopy width) of surviving seedlings were monitored.

Because variances in proportion data are not constant, a generalized linear model (GLM) was used to identify which seed trait had greatest influence on the success of direct seeding (seedling establishment after 1 year) and its components (germination, MLD and survival). Pearson's product-moment correlation was carried out to detect relationships between each component to direct seeding success. GLM was used to subsequently identify the impact of seed traits on each significant component. In addition, growth performance (height, root collar diameter and crown width) was considered to complement direct seeding success. ANOVA was used to detect the influence of seed traits on growth performance when the variance was constant; otherwise GLM was used. Post-hoc analyses for pair-wise comparisons of means were undertaken using Tukey's HSD test (*p*=0.05). All statistical analyses were performed using the statistical software R 2.11.1 (R Development Core Team, 2010).

Table 4.1 List of study species, collection and storage methods in both sites

Site[a]	Species[b]	Family	Collection method[c]	Storage methods (days storage)
KB	*Archidendron clyperia* (Jack) Niels.	Leguminosae	G	Open air, 27°C (9)
	Artocarpus dadah Miq.	Moraceae	G	Open air, 27°C (2)
	Cinnamomum iners Reinw. ex Bl.	Lauraceae	G	Refrigerator, 10°C (3)
	Callerya atropurpurea (Wall.) Schot	Leguminosae	G	Open air, 27°C (21)
	Garcinia hombroniana Pierre	Guttiferae	G	Open air, 27°C (4)
	Garcinia merguensis Wight	Guttiferae	G	Open air, 27°C (3)
	Lepisanthes rubiginosa (Roxb.) Leenh.	Sapindaceae	C	Refrigerator, 10°C (29)
	Litsea grandis (Wall. ex Nees) Hk.f.	Lauraceae	G	Refrigerator, 10°C (9)
	Pajanelia longifolia (Willd.) K. Sch.	Bignoniaceae	C	Open air, 27°C (60)
	Palaquium obovatum (Griff.) Engl.	Sapotaceae	G	Open air, 27°C (4)
	Scolopia spinosa (Roxb.) Warb.	Flacourtiaceae	G	Open air, 27°C (2)
NST	*Callerya atropurpurea* (Wall.) Schot	Leguminosae	G	Open air, 28°C (20)
	Diospyros oblonga Wall. ex G. Don	Ebenaceae	G	Open air, 28°C (4)
	Diospyros pilosanthera Blanco	Ebenaceae	G	Open air, 28°C (12)
	Garcinia cowa Roxb.	Guttiferae	G	Open air, 27°C (18)

Table 4.1 (Continued)

Site [a]	Species [b]	Family	Collection method [c]	Storage methods (days storage)
NST	*Microcos paniculata* L.	Tiliaceae	G,C	Open air, 28°C (10)
	Morinda elliptica (Hk.f.) Ridl.	Rubiaceae	G,C	Open air, 28°C (56)
	Peltophorum pterocarpum (DC.) Back. ex K. Hey.	Leguminosae	C	Open air, 28°C (17)
	Sandoricum koetjape (Burm.f.) Merr.	Meliaceae	G	Refrigerator, 10°C (56)
	Vitex pinnata L.	Verbenacea	C	Open air, 28°C (18)

[a] Site were sown: KB; Krabi; NST, Nakhon Si Thammarat

[b] Voucher specimens stored at CMU Herbarium, Chiang Mai University

[c] Collection methods: (G) from the ground; (C) from the crown

4.3 Results

The overall success of direct seeding was quantified as the number of live trees growing after one year per 100 seeds sown. All seed traits had some influence on direct seeding success. The seed traits of all 19 species tested are summarized in Table 4.2.

Seeds of 16 out of 19 species tested germinated and established seedlings in the field, 1 year after seed sowing, although the establishment rate varied among species from less than 10% to more than 40% (Figure 4.1).

The species could be divided into 4 fairly clear groups. The species that totally failed were *G. cowa*, *G. merguensis* and *P. longifolia*. Species with unacceptably low establishment (<10%) were *L. rubiginosa*, *M. elliptica*, *P. pterocarpum* and *S. koetjape*. Acceptable species (10-30%) were *A. clyperia*, *C. iners*, *D. pilosanthera*, *G. hombroniana*, *L. grandis*, *M. paniculata*, *P. obovatum*, *S. spinosa* and *V. pinnata*. Species with relatively high establishment (>30%) were *A. dadah*, *C. atropurpurea* and *D. oblonga*.

In general, species with higher establishment rates had large or intermediate sized seeds, round or oval seeds and seeds with moderate seed coats ($p<0.05$). Successful species also tended to be those with medium or low seed moisture content ($p<0.05$) (Figure 4.2).

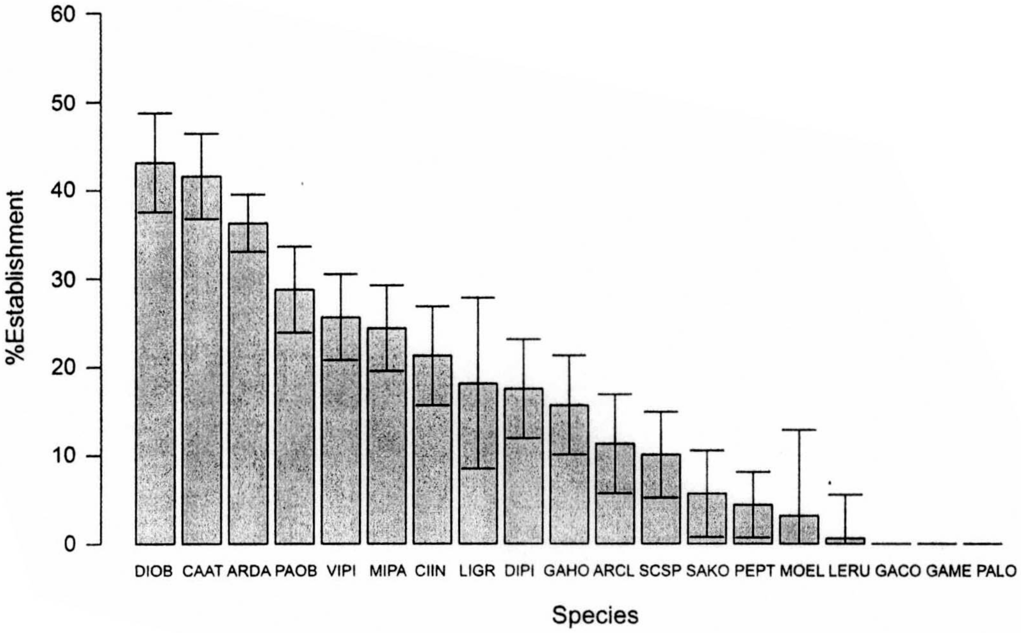

Figure 4.1 Mean seedling establishment of 16 species; ARCL = *A. clyperia*, ARDA = *A. dadah*, CAAT = *C. atropurpurea*, CIIN = *C. iners*, DIOB = *D. oblonga*, DIPI = *D. pilosanthera*, GAHO = *G. hombroniana*, LERU = *L. rubiginosa*, LIGR = *L. grandis*, MIPA = *M. paniculata*, MOEL = *M. elliptica*, PAOB = *P. obovatum*, PEPT = *P. pterocarpum*, SAKO = *S. koetjape*, SCSP = *S. spinosa* and VIPI = *V. pinnata*

Table 4.2 Seed traits of species used in the study

Species	Regeneration guild [a]	Size [b]	Shape [c]	Coat [d]	%MC [e]
Archidendron clyperia (Jack) Niels.	Pioneer of stem exclusion	I	R	Tn	M
Artocarpus dadah Miq.	Late-successional non-dominants	I	R	M	M
Callerya atropurpurea (Wall.) Schot	Late-successional non-dominants	L	R	Tk	M
Cinnamomum iners Reinw. ex Bl.	Late-successional non-dominants	I	R	Tn	L
Diospyros oblonga Wall. ex G. Don	Late-successional non-dominants	I	O	M	L
Diospyros pilosanthera Blanco	Late-successional non-dominants	I	O	M	L
Garcinia cowa Roxb.	Late-successional subcanopy	I	O	M	M
Garcinia hombroniana Pierre	Late-successional subcanopy	I	O	Tk	M
Garcinia merguensis Wight	Late-successional subcanopy	I	O	M	L
Lepisanthes rubiginosa (Roxb.) Leenh.	Late-successional subcanopy	I	R	M	H
Litsea grandis (Wall. ex Nees) Hk.f.	Late-successional subcanopy	I	R	M	M
Microcos paniculata L.	Pioneer of stem exclusion	I	R	Tk	L
Morinda elliptica (Hk.f.) Ridl.	Pioneer of stem exclusion	S	F	M	M
Pajanelia longifolia (Willd.) K. Sch.	Pioneer of stem exclusion	S	F	Tn	H
Palaquium obovatum (Griff.) Engl.	Late-successional subcanopy	I	O	M	M
Peltophorum pterocarpum (DC.) Back.	Pioneer of stem exclusion	S	F	M	L

Table 4.2 (Continued)

Species	Regeneration guild [a]	Size [b]	Shape [c]	Coat [d]	%MC [e]
Scolopia spinosa (Roxb.) Warb.	Late-successional subcanopy	S	R	Tn	M
Sandoricum koetjape (Burm.f.) Merr.	Late-successional non-dominants	I	R	Tk	M
Vitex pinnata L.	Late-successional subcanopy	I	R	Tk	L

[a] Regeneration guild (following criteria of Ashton et al., 2001)

[b] Seed size category based on seed weight: S=Small (<0.01–0.099 g); I=Intermediate (0.1–4.99 g); L=Large (>5.0 g) (seed size category determined from mean of a random sample of no less than 20 seeds per species) (Doust et al., 2006)

[c] Seed shape: R=Round (variance<0.06); O = Oval (variance= 0.06-0.09); F=Flat (variance >0.09)

[d] Seed coat thickness: Tn=Thin (<0.01-0.099 mm); M=Moderate (0.1-0.49 mm); Tk=Thick (>0.5 mm)

[e] %Moisture content: L=Low (0-35); M=Medium (36-70); H=High (71-100)

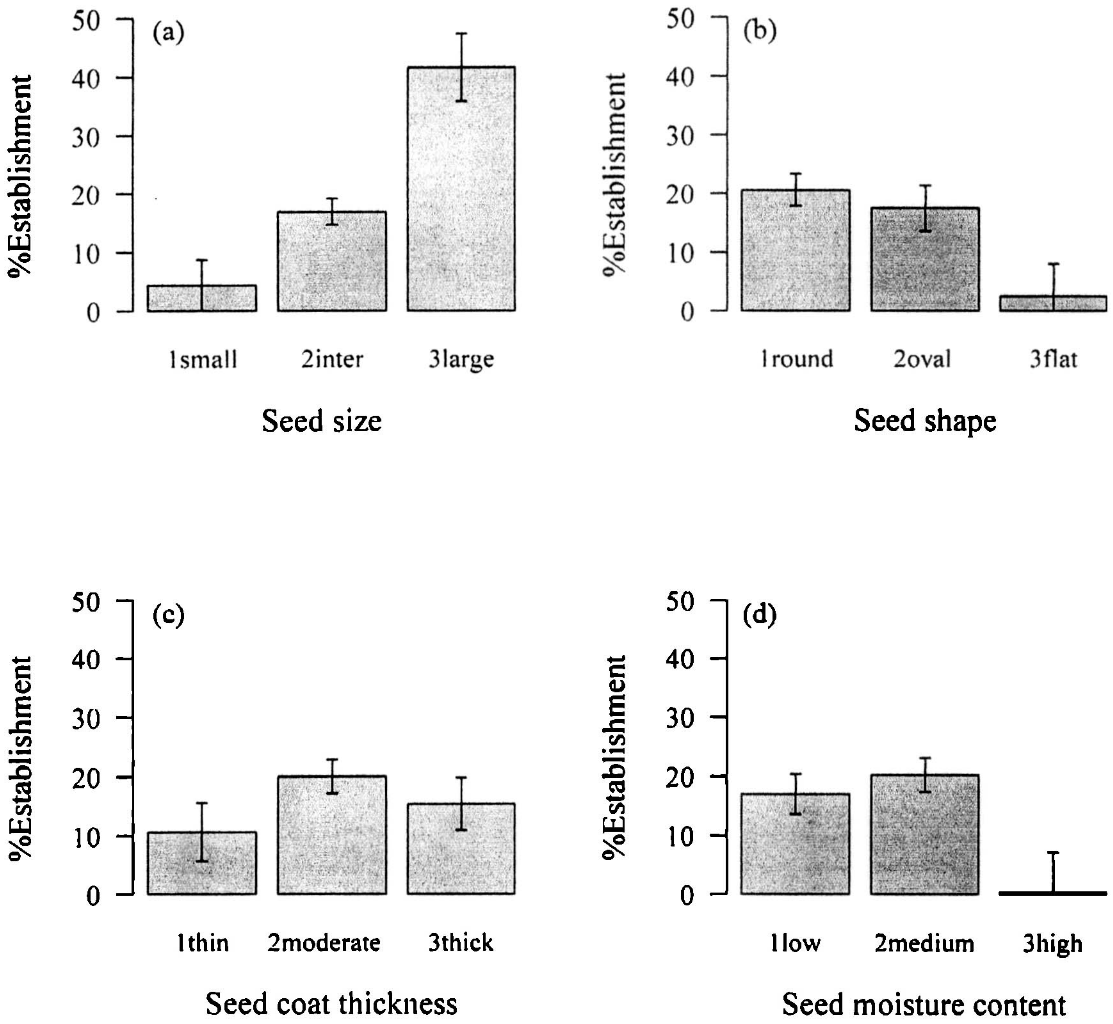

Figure 4.2 Mean seedling establishment influenced by (a) seed size; (b) seed shape; (c) seed coat thickness and (d) seed moisture content (p<0.05).

4.3.1 Impact of seed traits on the component of direct seeding success

Germination and survival were confirmed as the two main components of direct seeding success. There was a significantly positive relationship between germination and the number of live trees established after one year, per 100 seeds sown (r=0.39, p<0.001, N=85), and between survival and seedling establishment percentage (r=0.84, p<0.001, N=85), while no significant correlation was found between MLD and seedling establishment.

Although germination contributed to the success of direct seeding, it was less strength than seedling survival. Seed traits that resulted in significantly higher germination were intermediate and large seeds, and relatively round shape (p<0.05). All seed traits influenced seedling survival and consequently seedling establishment. Intermediate and large seeds showed significantly higher seedling survival percentage, along with round seeds, medium or low moisture content, and moderate coat thickness (p<0.05) (Table 4.3).

In overview, the climax species tend to have intermediate to large seed size and likely round shape with varied moisture content and seed coat thickness. They showed significantly about 2 times higher mean percentage establishment than pioneer species (27 and 13 % respectively) (p<0.05).

Table 4.3 Means of germination and survival percentage affected by seed traits

Component	Seed traits	Classes (No. of species in each classes)	Mean* (S.E.)
Germination	Size	Small (4)	40.00a (5.59)
		Intermediate (14)	54.92b (3.34)
		Large (1)	62.11b (3.37)
	Shape	Round (10)	57.43b (2.81)
		Oval (6)	51.25ab (6.56)
		Flat (3)	37.50a (6.32)
Seedling Survival	Size	Small (4)	10.33a (4.28)
		Intermediate (14)	26.09b (3.36)
		Large (1)	65.41b (6.00)
	Shape	Round (10)	32.45b (4.18)
		Oval (6)	24.70ab (5.28)
		Flat (3)	11.40a (5.32)
	Coat	Thin (4)	12.04a (4.02)
		Moderate (10)	31.21b (4.16)
		Thick (5)	29.88ab (6.39)
	Moisture content	Low (7)	30.08b (4.91)
		Medium (10)	29.99b (4.18)
		High (2)	0.89a (0.89)

* Same letters are not different (p>0.05) using treatment contrasts.

4.3.2 Influence of seed traits on seedling growth

By the end of the study, seedlings germinated from seeds with thin seed coats had significantly larger root collar diameters (RCD) than those germinated from seeds with moderate or thick coats ($p<0.05$). Small seeds tended to give rise to seedlings with broader crowns, whereas flat seeds tended to produce taller seedlings with broader crowns ($p<0.05$) (Figure 4.3).

There was no relationship between dormancy period and the growth performance of direct-seeded seedling at one year after sowing. Seed traits that contributed to better growth performance, some of them also contributed to shorter dormancy. In general, seeds with shorter dormancy tended to be smaller, with thin seed coats and higher moisture content ($p<0.05$) (Table 4.4).

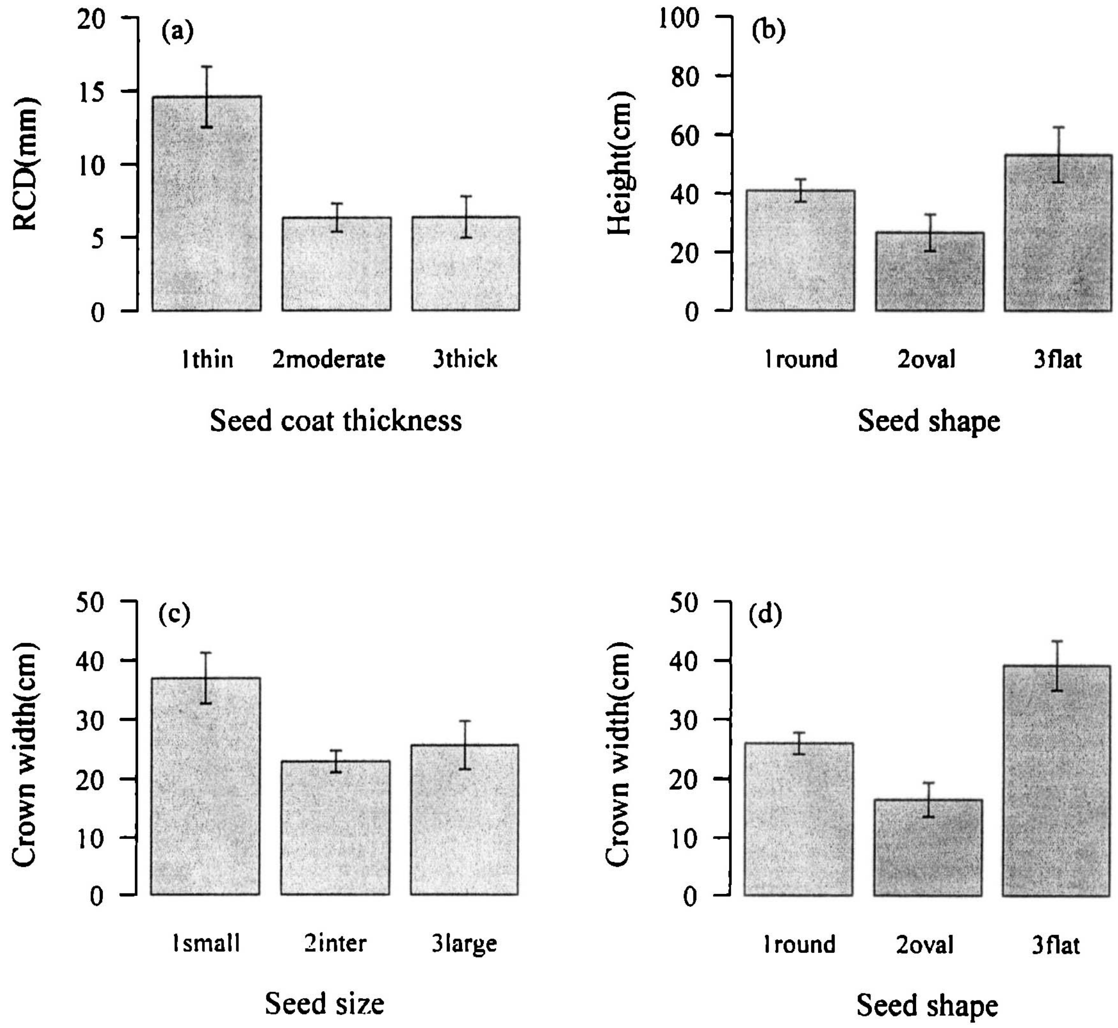

Figure 4.3 Effects of seed traits on seedling growth and development (a) effects of seed coat thickness on final RCD, (b) effects of seed shape on final height; (c) effects of seed size on mean crown width and (d) effects of seed shape on crown width ($p<0.05$).

Table 4.4 Mean MLD (days) influenced by seed traits

Seed traits	Classes (No. of species in each classes)	Mean* (S.E.)
Size	Small (4)	46.12a (16.52)
	Intermediate (14)	38.40ab (3.82)
	Large (1)	131.22b (6.66)
Shape	Round (10)	44.41a (6.27)
	Oval (6)	56.58a (7.74)
	Flat (3)	57.42a (21.21)
Coat	Thin (4)	10.75a (0.74)
	Moderate (10)	66.26b (7.89)
	Thick (5)	40.20b (2.42)
Moisture content	Low (7)	60.44b (9.32)
	Medium (10)	48.91b (6.60)
	High (2)	11.00a (1.00)

* Same letters are not different ($p>0.05$) using treatment contrasts.

4.3.3 Using seed traits for species selection

Seeds with intermediate to large size and oval to round shape showed excellence in the field for germination, survival and recruitment success at one year after sowing. These traits could be used to predict high potential candidate (Table 4.6) for direct seeding in southern Thailand (e.g. *A. dadah*, *C. atropurpurea* and *D. oblonga*). In addition, seeds with low to medium moisture content could be used to predict the candidate with medium potential (Table 4.5) e.g. *P. obovatum* and *V. pinnata*.

In contrast, small, flat seeds with high moisture content tended to be not so suitable as candidates for direct seeding, since they achieved a significantly lower germination and seedling survival percentages than species with other seed traits (p<0.05) (Table 4.4 and 4.6) e.g. *L. rubiginosa* and *P. longifolia*, resulting in very low establishment percentage by one year after sowing. Seed coat was not a very strong predictor of direct seeding success since species in all three classes of seed coat thickness showed medium establishment (Table 4.5) (e.g. *C. iners*, *M. paniculata* and *L. grandis*).

In addition, all potential traits (size, dryness and shape) were combined to calculate a seed traits index (Table 4.6). Early achievement of direct seeding, establishment percentage and height of survived seedlings at one year after sowing, were used to calculate suitability score (Table 4.7). There was a significantly weak relationship between seed traits index and suitability score at one year after sowing (r=0.47, p<0.05) (Figure 4.4a), however the relationship was stronger if an outlier (*A. dadah*) was removed (r=0.70, p<0.05) (Figure 4.4b).

Table 4.5 Summary of seed traits and their potential to be the candidates for direct seeding

Seed traits	Establishment [a]	Germination [b]	Survival [c]	Potential
Size				
Small				Low
Intermediate	*	*	*	High
Large	*	*	*	High
Shape				
Round	*	*	*	High
Oval	*	*	*	High
Flat				Low
Coat				
Thin	*			Medium
Moderate	*		*	Medium
Thick	*		*	Medium
Moisture content				
Low	*		*	Medium
Medium	*		*	Medium
High				Low

[a] An asterisk presents if $\geq 50\%$ of tested species in each trait achieved acceptable or good establishment at one year after sowing

[b] An asterisk presents if significantly higher germination percentage

[c] An asterisk presents if significantly higher survival percentage

Table 4.6 Seed traits score of studied species

Species	Rank size (0-100)	Rank dryness (0-100)	Rank shape (0-100)	Raw seed traits index [a] (0-300)	Rank seed traits index (0-100)
C. atropurpurea	100.00	73.36	96.00	269.37	100.00
V. pinnata	0.33	100.00	100.00	200.33	74.37
C. iners	0.34	90.68	97.02	188.04	69.81
M. paniculata	0.79	90.26	95.57	186.62	69.28
A. dadah	0.61	81.74	98.86	181.22	67.27
L. grandis	0.50	81.17	87.74	169.41	62.89
G. cowa	1.70	93.66	73.08	168.44	62.53
S. koetjape	3.28	79.98	83.04	166.30	61.74
A. clyperia	0.81	79.29	85.74	165.84	61.57
D. oblonga	1.06	92.52	66.72	160.30	59.51
G. merguensis	0.50	91.90	67.71	160.11	59.44
D. pilosanthera	0.62	82.50	67.46	150.58	55.90
S. spinosa	0.11	51.73	89.03	140.87	52.30
P. obovatum	2.24	61.53	74.68	138.46	51.40
L. rubiginosa	0.39	36.92	89.57	126.88	47.10
P. pterocarpum	0.06	90.77	35.45	126.28	46.88
G. hombroniana	6.11	44.21	70.51	120.83	44.86
M. elliptica	0.03	50.63	47.44	98.10	36.42
P. longifolia	0.01	11.63	7.75	19.39	7.20

[a] Raw seed traits index means sum of rank size, rank dryness and rank shape.

Table 4.7 Suitability score of studied species at one year after sowing

Species	Establishment (%)	Height (cm)	Raw suitability score (E*H)[a]	Rank Suitability score (0-100)
A. dadah	36.25	83.03	3009.76	100.00
C. atropurpurea	41.57	28.97	1204.30	40.01
V. pinnata	25.63	44.29	1134.97	37.71
P. obovatum	28.75	34.95	1004.73	33.38
D. oblonga	43.13	20.57	887.13	29.47
M. paniculata	24.38	30.30	738.45	24.54
C. iners	21.25	31.16	662.13	22.00
G. hombroniana	15.63	40.90	639.06	21.23
L. grandis	18.13	30.34	549.95	18.27
A. clyperia	11.25	46.14	519.06	17.25
D. pilosanthera	17.50	14.03	245.47	8.16
S. koetjape	5.63	42.98	241.74	8.03
S. spinosa	10.00	24.06	240.63	7.99
P. pterocarpum	4.38	35.83	156.77	5.21
M. elliptica	3.13	45.44	142.01	4.72
L. rubiginosa	0.63	15.00	9.38	0.31

[a] Raw suitability score means establishment percentage multiply by height.

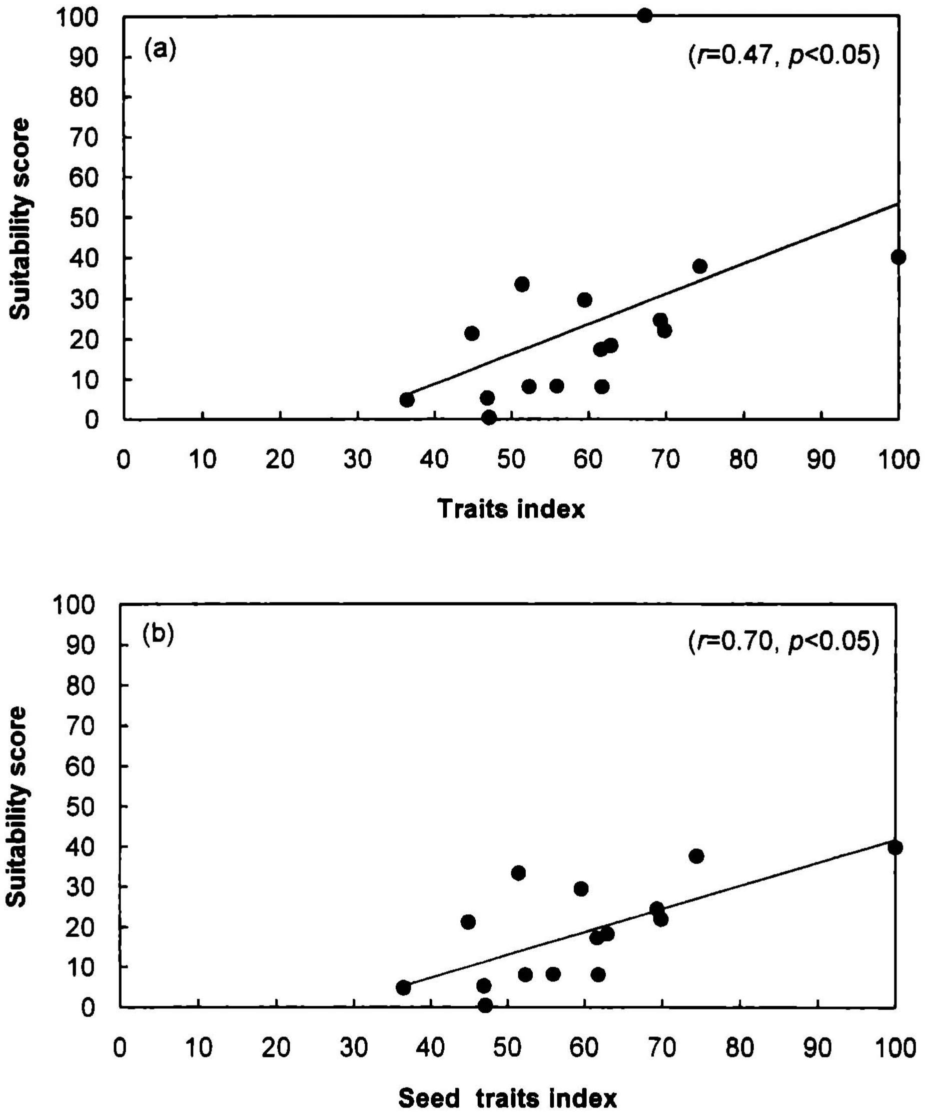

Figure 4.4 Correlation between combined seed traits index and suitability score; (a) all survived species and (b) all survived species without *A. dadah*

4.4 Discussion

Seed traits can be used to predict direct seeding success, because according to our results, seeds with intermediate to large size with round shape showed excellent establishment in the field one year after sowing. The key advantage of large seeds appears to be their tolerance of stresses since higher resources can be allocated to tolerate particular stresses such drought or shade, however this advantage does not appear uniformly under all conditions (Coomes & Grubb, 2003; Muller-Landau, 2010) or each stage of life cycle (Kleijn, 2003). Seed mass data for 12,987 species on the seed plant phylogeny were arrayed and indicated that wide divergences in seed size were more often associated with divergences in growth form than with divergences in dispersal syndrome or latitude (Moles et al., 2005). Seed shape had been proposed as a good indicator for predicting seed persistence, although the results varied with different sites (Liu et al., 2007; Peco et al., 2003; Yu et al., 2007), however it had been shown that seed shape is positively and significantly related to germination (Liu et al., 2007). Compact and round seeds can easily penetrate cracks in the soil, and thus escape post-dispersal predation (Yu et al., 2007), less susceptible to seed desiccation, and therefore possibly contributed to the establishment success.

Seed size influences early after germination, for cotyledon-stage seedlings, survival is influenced mostly by stored reserves and by initial seedling size (Leishman & Westoby, 1994; Saverimuttu & Westoby, 1996) while later on, growth and survival are largely determined by seedling morphology and physiology (Grubb & Metcalfe, 1996; Saverimuttu & Westoby, 1996). Successful seedling establishment is the primary goal of direct seeding. In seasonally dry tropical climates, the main factors influencing seedling establishment by direct seeding are i) germination capability under the harsh conditions just before or at the beginning of the rainy season and ii) survival through the first subsequent dry season. This study shows that certain seed traits may favour high germination and seedling survival rates.

Large seed size, which is generally a frequent characteristic of seeds of shade-tolerant species (Slik, 2005), was associated with high germination, with seedlings exhibiting high survival and consequently high overall seedling establishment rates, one year after direct seeding on a degraded site in southern Thailand (e.g. *C. atropurpurea*). This may be because the high energy reserves contained within larger seeds allow them to remain viable for longer in unsuitable environments (Muller-Landau, 2010; Osunkoya et al., 1994). Large size is also associated with avoidance of seed predation (Mack, 1998). The results presented here agree with those of Moles and Westoby (2006), who reported that, during juvenile stage, seedlings germinating from larger seeds generally exhibit higher survival and seedling recruitment rates. Even within species, larger seeds tend to have higher germination and seedling survival rates (Cicek & Tilki, 2007; Eriksson, 1999; Manga & Sen, 1995).

In contrast to Doust et al. (2008), species with intermediate seed size (both pioneer and climax species) showed comparatively high establishment rates, this is possibly because other seed traits should be considered when selecting species for direct seeding. Nevertheless, seed size was found to be an important factor affecting establishment in relation to micro-site conditions (Doust et al., 2006).

Of the 14 species with intermediate-sized seeds, tested in this study, all had likely round seeds and high establishment percentages (e.g. *A. dadah*, *L. grandis* and *V. pinnata*). Insect predation is common in disturbed forests and open areas (De Menezes et al., 2010). Insects may have difficulty with processing round, intermediately-sized seeds, which might explain why such seeds had relatively high germination rates, since there was a higher probability that more seeds would be left in the soil (Van Ulft, 2004). In addition, round intermediate-sized seeds tended to produce robust seedlings with relative high rates of survival and establishment. In contrast, flat- and small-seeded tend to have high fecundity but low stress-tolerance (Moles & Westoby, 2006; Muller-Landau, 2010).

Seeds with high moisture content are common in wet climates and they produce rather fragile seedlings that can survive in their natural habitats. Desiccation is the main cause of early seedling mortality, particularly damp-soil species (Laman, 1995; Sacchi & Price, 1992). Only one species with seeds of high moisture content (*L. rubiginosa*) could establish. Therefore, seeds with medium and low moisture contents are a better choice for direct seeding in the open areas. Seed coat thickness was not associated with the success of direct seeding, because establishment percentages were relatively equal for all seed-coat classes.

In addition to high seedling recruitment, fast-growth is also need for successful direct seeding in order for the seedlings to out-compete surrounding vegetation. Seed size, coat thickness and shape all influenced to the growth performance of seedlings one year after sowing. Species with small seeds created bigger crowns, whereas thin-coated seeds gave rise to seedlings with larger RCD's. Flat-seeded species showed bigger crown and taller seedlings.

All species with flat seeds also had small-seeded size and they were identified as low potential candidates for direct seeding because of their low establishment percentage. However, the survival seedlings performed fascinating growth in the field with varied MLD. Small seeds had short dormancy (except *P. pterocarpum*), they become dependent on external resources very quickly, and their priority may therefore be to photosynthesize as soon as possible (Van Ulft, 2004). This enables them to develop roots quickly and so gain access to external sources of minerals. Consequently, species with small seeds, such as *M. elliptica* and *S. spinosa* showed comparatively large crown. Similarly, species with thin-coated seeds are also short dormancy; they produced bigger RCD (e.g. *C. iners*).

Remarkably, all Legume species (*A. clyperia*, *C. atropurpurea* and *P. pterocarpum*) although they varied in seed size and seed coat thickness; all success fully established in degraded areas and showed high growth performance, because they can fix atmospheric nitrogen by bacteria in their root nodules (Engel & Parrotta, 2001).

In summary, seed size, shape and moisture content can be used as guidelines for selecting potential candidate for direct seeding. Species with seed traits index higher than 50 were successful species with higher suitability score, except *D. pilosanthera*, *G. cowa*, *G. hombroniana*, *G. merguensis*, *S. koetjape* and *S. spinosa*; their relative success could not be predicted from seed traits. Species having oval to round, large or intermediate-sized seeds and with low or medium moisture contents are more likely to be worth testing for direct seeding success than those with other seed traits or species selected at random. These factors explained direct seeding success (or lack therefore) in 13 out of the 19 tested species (i.e. 70%). The thirteen species that could be predicted from seed traits could be divided into 2 groups; 9 recommended species for direct seeding on degraded areas in southern Thailand: *A.*

clyperia, *A. dadah*, *C. atropurpurea*, *C. iners*, *D. oblonga*, *L. grandis*, *M. paniculata*, *P. obovatum* and *V. pinnata*; and 4 other species (*L. rubiginosa*, *M. elliptica*, *P. longifolia* and *P. pterocarpum*) which should be excluded from the list of candidates. Seed coat thickness was not a useful trait for predicting suitable species for direct seeding. However, the climax species, *G. hombroniana* and *S. spinosa* achieved acceptable establishment, including *M. elliptica* and *P. pterocarpum* seedlings which had growth in the field after surviving the 1st dry season; they should be added to the list of 9 recommended species above. For both shade-tolant and gap-demanding trees in tropical lowland forest, greater seed size provides greater tolerance of hazards, particularly on degraded areas in southern Thailand.

Chapter 5

Factors affecting the establishment of direct-seeded seedlings

5.1 Introduction

Natural regeneration in degraded areas is often a slow process, especially if limited by lack of seed sources and unsuitable conditions for seed germination and seedling establishment. Lack of dispersal of forest tree seeds and competition between tree seedlings and grasses and herbs are the most important barriers to forest succession (Holl et al., 2000). Other factors can include high seed predation (Hammond, 1995; Hau, 1997; Zimmerman et al., 2000), low seed germination rates (Garcia-Orth & Martínez-Ramos, 2008; Hau & Corlett, 2003), and lack of nutrients (Cole et al., 2011) and soil moisture (Fenner & Thompson, 2005).

Successful strategies to facilitate recovery on degraded areas must simultaneously overcome all obstacles. Direct seeding is a low-cost technique for restoration, which can increase plant species richness in restored sites. However, results of direct seeding can be unpredictable, due to a multitude of unfavourable biotic and abiotic factors. Tropical rain forest trees are notable for having seeds with short viability (Schmidt, 2007). Therefore, substantial losses of viable seeds from the seed bank occur because of seed aging and death, germination failure, predation and diseases (Kozlowski, 2002). A study of 100 tree species, native to the seasonal moist tropical forest in Panama, found only 12 species had a median length of germination time more than 120 days (Sautu et al., 2006) and many were highly sensitive to desiccation (Vazquez-Yanes & Orozco-Segovia, 1993).

Direct seeding might overcome the lack of a seed source, but seed predation is another barrier for regeneration on degraded areas. It is a significant factor in reducing the amount of seeds available for seedling recruitment in degraded hillside in Hong

Kong (Hau, 1997), abandoned tropical humid pastures (Hammond, 1995) as well as tropical dry forest (Zimmerman et al., 2000). The probability of seed predation depends on seed characteristics, such as animal preferences, energetic and chemical content, seed mass (Carmago et al., 2002) and abundance of potential seed predators (Nepstad et al., 1996). Few studies have explored the potential implications of predator exclusion as a way of increasing seedling establishment (Notman & Gorchov, 2001). Seed predator exclusion seems to increase seed survival in abandoned pastures substantially (Garcia-Orth & Martínez-Ramos, 2008; Notman & Gorchov, 2001). However, exclusion of rodent seed predators may still leave the seeds vulnerable to small predators such as ants (Woods & Elliott, 2004).

Apart from seed predation, low germination rate is another impediment to natural regeneration, especially on degraded areas where the environments are harsh (Garcia-Orth & Martínez-Ramos, 2008). In Hong Kong, seed germination of 6 native tree species in the nursery was 4-15 times higher than on degraded hillsides (Hau, 1999). Soil moisture is an important factor affecting seed germination in degraded forest land (Fenner & Thompson, 2005) and seed germination was sharply reduced by lack of rainfall (Hardwick et al., 1997). Lack of suitable micro-sites for seed germination is likely to limit recruitment of naturally dispersed tree species on degraded sites. Degree of compaction and fertility did not affect the rate of germination of a pioneer rain forest species in gully sites but significantly influenced survival and growth of germinated seedlings (Sun et al., 1995). Burying seeds resulted in high establishment rates from direct seeding of tropical rain forest species (Doust et al., 2006) and significantly increased germination percentage of direct sown seeds (Cole, 2009; Cole et al., 2011; Woods & Elliott, 2004) on degraded areas. In addition, burying seeds reduces predation in abandoned pastures in Mexico (Garcia-Orth & Martínez-Ramos, 2008) and contributes to the development of secondary vegetation (Guariguata & Ostertag, 2001).

After germination, young seedlings have to face several obstacles before being able to establish well. A major cause of mortality in seedlings is competition from surrounding vegetation. Competition for light, water and nutrients can be intense even in short turf or apparently sparse vegetation (Fenner & Thompson, 2005). Direct seeding of a pioneer species in tropical northern Australia demonstrated that weed competition significantly influences survival and growth of germinated seedlings. Seedlings had the lowest biomass when grown with weeds (Sun et al., 1995). Various sowing treatments had limited effect on weed recolonisation, however burying seeds under mulch resulted in shorter weeds on a degraded lowland site in the Australian wet tropics (Doust et al., 2006; Snell & Brooks, 1997). In addition to sowing treatment, late sowing time in the rainy season may be preferable for sites where intensive maintenance is not practicable because weeds have less time to grow before the subsequent dry period (Doust et al., 2008).

Lack of moisture is another common cause of seedling mortality (Fenner & Thompson, 2005), which may seriously affect the maintenance of biodiversity, especially on degraded areas or fragmented forest (Renison et al., 2005). In a study of regeneration of *Salix lasiolepis* in Arizona, mortality of first-year seedlings due to desiccation approached 100% (Sacchi & Price, 1992). A study of planted native tree seedlings on a degraded hillside in Hong Kong showed that mortality was not reduced by irrigation (Hau & Corlett, 2003), even though most mortality occurred in the dry season.

Soil properties also affect the growth and species composition of colonists on deforested land. One of the most significant impacts is the loss of soil structure, as evidenced by increases in bulk density and decreases in soil porosity (Guariguata & Ostertag, 2001). A variety of chemical changes also occur after land conversion, but it is more difficult to generalize about the direction of these processes. However, N is mainly lost through biomass removal, volatilization during burning, denitrification, and leaching (Keller et al., 1993). Direct-seeded seedlings of late-successional species had lower total biomass in recently abandoned pasture, compared with young mixed-species tree plantations, probably due to differences in nutrient availability between habitats (Cole et al., 2011). Adding fertilizer to planted seedlings did not affect their survival, but enhanced early seedling growth on degraded hillside grassland in Hong Kong (Hau & Corlett, 2003).

Despite several studies that have shown the advantages of using large seeded species, small-seeded pioneer species have commonly been used to restore forest ecosystems, because they occur naturally at the early stages of succession (Balandier et al., 2009; Engel & Parrotta, 2001; Garcia-Orth & Martínez-Ramos, 2008; Sun et al., 1995). A few previous studies suggest that it is a promising restoration strategy for larger-seeded tree species (Carmago et al., 2002; Doust et al., 2006; Hardwick, 1999) but the results were vary among different habitats. Direct seeding of late-successional tree species had greater total biomass and lower root:shoot ratios in mixed species plantation (Cole et al., 2011) and it has been emphasized that the efficacy of sowing large seeds will depend on site characteristics (Garcia-Orth & Martínez-Ramos, 2008). Some characteristics have been suggested to give the most promising result, such as easily available seeds (Cole et al., 2011), high seed quality (Engel & Parrotta, 2001), rapid and consistent germination (Tunjai, 2005), deep root extension (Doust et al., 2008), and high growth rate potential (Woods & Elliott, 2004). Direct sowing a range of species which vary in their seed morphology and ecological niches for establishment will be difficult to achieve with a single sowing event (Doust et al., 2008).

Seed storage is a common problem for many tropical forest trees, since their seeds are recalcitrant or intermediate, meaning that they are sensitive to desiccation and often to low temperature, conditions traditionally considered necessary for long-term seed storage. For example for short-term storage, Woods and Elliott (2004) used airtight jars to store seeds at room temperature (26-28 ° C) out of direct sunlight for approximately one week for *Lithocarpus elegan*, *Spondias axillaris* and *Sapindus rarak*, and 1.5 months for *Erythrina subumbran* before sowing them into the soil. They reported that *E. subumbran* showed low germination percentage because of low seed viability, it was probably due to improper storage and this reflects the challenges of using recalcitrant seeds for forest restoration projects. Further research on seed storage is particularly important if direct seeding is to be applied to species that fruit and disperse their seeds at times other than at the beginning of the rainy season to ensure that seeds do not lost their ability for germination at the time of sowing (Tunjai, 2005).

Previous studies highlighted the fact that more systematic trials are needed to identify suitable sowing and management regimes for cost-effective reforestation by direct seeding. No studies on direct seeding have been carried out in southern Thailand. The aims of the experiment reported here were i) to test if the germination, establishment and growth performance of direct-seeded species in southern Thailand are affected by seed storage, different sowing times, mulching, soil nutrient supply and seed predator exclusion, and ii) to determine barriers that might slow down successional process on abandoned areas.

5.2 Materials and Methods

5.2.1 Experimental design

Seed collection was undertaken at most two months prior to each sowing time (early and late in the rainy season) in each study site. A total of 30 species was tested in the study, 20 species was tested at KB (10 species for early sowing and 10 other species for late sowing), 14 species at NST (9 species for early sowing and 10 species for late sowing with 5 species overlapping between both sowing times), and 4 species were available at both sites (Table 5.1). A total 320 seeds of each species was used per sowing event. A total of 640 seeds each of *D. oblonga*, *D. pilosanthera* and *M. elliptica* was sown at both sowing times at NST, 640 seeds each of *M. paniculata* and *T. citrina* were sown at both sites and 960 seeds each of *P. pterocarpum* and *V. pinnata* were sown at both sowing times at NST plus late sowing at KB. Seeds of 3 species (*D. oblonga*, *D. pilosanthera* and *P. pterocarpum*) were stored in refrigerator, 10°C for about 3 months before subsequently being sown at the late sowing time at NST. Seeds collected from KB were sown only at KB and likewise for NST species for both sowing times. Direct seeding experiments were established in May and October 2009 for KB site, and in September and December 2009 for NST site, corresponding with the beginning and end of the rainy season. Existing weed growth was cleared via tractor prior to trial establishment in both field sites.

At each site, 8 blocks (4 m x 80 m) were established, four blocks, about 8 m apart, were selected for early sowing time and other four blocks were left for the late sowing. Each block was subdivided into four 4 m x 20 m experimental plots, to which one treatment of mulching and soil nutrient supply were randomly allocated. Experimental plots were further subdivided into ten sub-plots (2 m x 4 m) to randomly accommodate different species, 20 seeds per each sub-plot. Half of each sub-plot was covered with mosquito netting to exclude small vertebrates and ants after seed burial. Seeds were buried to an approximate depth of 3-45 mm depending on seed size.

About 4 to 6 weeks after the seeds were sown, hand weeding was done with additional fertilizer following the treatments, three times or once for early and late sowing respectively. Organic fertiliser, "Mod Bai Mai" brand was used (20 g per seedling), it has been advertised to help on improving physical, chemical and biological soil structure. Moreover, the fertiliser can adjust soil pH to be a suitable condition for plants to absorb nutrients, and also help on retaining soil moisture. The Center for Scientific and Technological Equipments, Walailak University had analyzed the fertiliser and reported pH 7.1, 1.52 % total Nitrogen, 0.39 % total P_2O_5 and 1.42 % total K_2O.

Weeding at the NST site was reduced from three to two times for early sowing, due to continuingly heavy rains in the area. Germination (defined as radicle emergence and seed germination) was monitored weekly until 4 weeks without germination (after a clear peak had occurred). Germination percentage and median length of dormancy (MLD) were calculated for each seed batch. MLD reflects seed dormancy as the length of time between sowing and germination of half the seeds which eventually germinate (FORRU, 2008a) for each replicate. In addition, growth performance (root collar diameter (RCD), height and canopy width) and survival of seedlings were measured after the first dry season. In the nursery, four replicates of 100 seeds were sown at ambient temperature. Seed germination was monitored weekly similar to the field.

5.2.2 Statistical analysis

A Generalized Linear Model (GLM) was used to identify the impact of sowing time, mulching, soil nutrient supply and seed exclusion on germination and establishment percentage and MLD due to non-constant variance in proportion and count data. ANOVA was used to analyse growth data (RCD, height and canopy width). Seedling growth data were transformed when heterogeneity or non-normality was detected, or outliers were subsequently removed to meet the assumptions of an ANOVA, otherwise GLM was used. Mean comparisons were carried out by treatment contrast (p=0.05). All statistical analyses were performed using the statistical software R 2.11.1 (R Development Core Team, 2010).

Table 5.1 List of study species, sowing time and storage methods at both sites

Species [a]	Family	Seed collection date	Storage methods	Days of storage	Sowing time [b]
Alstonia macrophylla Wall. ex G. Don	Apocynaceae	20 Aug 09	Open air, 27°C	60	L1
Antidesma montanum Bl.	Euphorbiaceae	19 Oct 09	Refrigerator, 10°C	1	L1
Aporosa sp.	Euphorbiaceae	8 Dec 2009	Open air, 28°C	1	L2
Archidendron clyperia (Jack) Niels.	Leguminosae	6 May 09	Open air, 27°C	9	E1
Artocarpus dadah Miq.	Moraceae	13 May 09	Open air, 27°C	2	E1
Callerya atropurpurea (Wall.) Schot	Leguminosae	20 Sep 09	Open air, 28°C	20	E2
Calophyllum soulattri Burm. f.	Guttiferae	19 Oct 09	Open air, 27°C	1	L1
Canthium glabrum Bl.	Rubiaceae	8 Dec 09	Open air, 28°C	1	L2
Cinnamomum iners Reinw. ex Bl.	Lauraceae	12 May 09	Refrigerator, 10°C	3	E1
Diospyros oblonga Wall. ex G. Don	Ebenaceae	16 Sep 09	Refrigerator, 10°C	4, 85	E2,L2
Diospyros pilosanthera Blanco	Ebenaceae	8 Sep 09	Refrigerator, 10°C	12, 93	E2,L2
Elaeocarpus stipularis Bl.	Elaeocarpaceae	6 Dec 09	Open air, 28°C	3	L2
Fagraea fragrans Roxb.	Loganiaceae	19 Oct 09	Open air, 27°C	1	L1
Garcinia cowa Roxb.	Guttiferae	2 Sep 09	Open air, 28°C	18	E2
Garcinia hombroniana Pierre	Guttiferae	11 May 09	Open air, 27°C	4	E1
Garcinia merguensis Wight	Guttiferae	12 May 09	Open air, 27°C	3	E1
Horsfieldia irya (Gaertn.) Warb.	Myristicaceae	19 Oct 09	Open air, 27°C	1	L1
Lepisanthes rubiginosa (Roxb.) Leenh.	Sapindaceae	16 Apr 09	Refrigerator, 10°C	29	E1

Table 5.1 (Continued)

Species [a]	Family	Seed collection date	Storage methods	Days of storage	Sowing time [b]
Litsea grandis (Wall. ex Nees) Hk.f.	Lauraceae	6 May 09	Refrigerator, 10°C	9	E1
Microcos paniculata L.	Tiliaceae	10 Sep, 19 Oct 09	Open air, 28°C	10, 1	E2,L1
Morinda elliptica (Hk.f.) Ridl.	Rubiaceae	26 Jul, 8 Dec 09	Open air, 28°C	56, 1	E2,L2
Pajanelia longifolia (Willd.) K. Sch.	Bignoniaceae	16 Mar 09	Open air, 27°C	60	E1
Palaquium obovatum (Griff.) Engl.	Sapotaceae	11 May 09	Open air, 27°C	4	E1
Peltophorum pterocarpum (DC.) Back. ex K. Hey.	Leguminosae	4 Sep, 3 Sep and 3 Sep 09	Open air, 28°C/ Refrigerator, 10°C	46, 17 and 97	L1,E2,L2
Sandoricum koetjape (Burm.f.) Merr.	Meliaceae	26 Jul 09	Refrigerator, 10°C	56	E2
Scolopia spinosa (Roxb.) Warb.	Flacourtiaceae	13 May 09	Open air, 27°C	2	E1
Sindora siamensis Teysm. ex Miq.	Leguminosae	30 Sep 09	Open air, 27°C	20	L1
Symplocos macrophylla Wall. ex DC.	Symplocaceae	8 Dec 09	Open air, 28°C	1	L2
Terminalia citrina (Gaerth.) Rox. Ex	Combretaceae	22 Oct, 6 Dec 09	Open air, 27/28°C	1, 3	L1,L2
Vitex pinnata L.	Verbenacea	22 Sep, 2 Sep and 8 Dec 09	Open air, 27/28°C	28, 18 and 1	L1,E2,L2

[a] Voucher specimens stored at CMU Herbarium, Chiang Mai University

[b] Sowing time: E1= Early sowing (May 2009); L1 = Late sowing (October 2009) in Krabi; E2 = Early sowing (September 2009); L2 = Late sowing (December 2009) in Nakhon Si Thammarat

5.3 Results

A total of 25 species germinated in the field, with germination per cent ranging from 7 to 90%. Four species: *A. montanum*, *Aporosa* sp., *F. fragrans* and *H. irya* germinated only in the nursery, with low germination per cent (Table 5.2 and 5.3). No seeds of *S. macrophylla* germinated in both field and nursery.

Table 5.2 Mean percentage germination of all studied species in both field and nursery condition at Krabi (S.E.)

Species	Field		Nursery	
	Early	Late	Early	Late
Alstonia macrophylla	-	40.00 (2.22)	-	62.50 (2.90)
Antidesma montanum		0		3.00 (1.22)
Archidendron clyperia	63.13 (3.40)		37.00 (7.31)	
Artocarpus dadah	72.50 (2.45)		51.75 (4.85)	-
Calophyllum soulattri		25.31 (5.76)		65.75 (2.66)
Cinnamomum iners	48.75 (1.69)	-	36.00 (1.68)	
Fagraea fragrans		0		12.50 (2.22)
Garcinia hombroniana	72.19 (4.16)		80.75 (5.36)	
Garcinia merguensis	20.63 (4.16)	-	12.00 (1.78)	
Horsfieldia irya	-	0		39.50 (1.50)
Lepisanthes rubiginosa	47.19 (7.45)		36.75 (1.11)	-
Litsea grandis	55.31 (4.66)	-	39.00 (4.42)	
Microcos paniculata		9.69 (1.56)	-	15.75 (3.15)
Pajanelia longifolia	35.31 (4.46)		20.25 (3.61)	
Palaquium obovatum	43.44 (4.74)		46.25 (4.39)	
Peltophorum pterocarpum		26.56 (2.86)		14.00 (1.58)
Scolopia spinosa	48.13 (6.09)		45.75 (2.29)	
Sindora siamensis	-	24.38 (1.65)		15.00 (2.00)
Terminalia citrina		0		11.25 (2.53)
Vitex pinnata	-	17.50 (3.89)	-	23.75 (3.97)

Table 5.3 Mean germination percentage of all studied species in both field and nursery condition at Nakhon Si Thammarat (S.E.)

Species	Field		Nursery	
	Early	Late	Early	Late
Aporosa sp.	-	0	-	1.00 (0.41)
Callerya atropurpurea	62.19 (7.86)		47.25 (1.93)	
Canthium glabrum		31.88 (2.91)	-	50.50 (2.18)
Diospyros oblonga	82.19 (1.29)	7.81 (2.25)	88.25 (1.25)	7.00 (1.35)
Diospyros pilosanthera	90.31 (3.12)	23.13 (2.42)	89.75 (1.03)	13.50 (2.33)
Elaeocarpus stipularis	-	18.44 (2.36)		21.00 (2.00)
Garcinia cowa	30.00 (2.84)		26.25 (5.74)	-
Microcos paniculata	61.56 (1.18)		50.75 (4.21)	-
Morinda elliptica	69.38 (3.29)	17.81 (5.14)	54.67 (8.52)	31.00 (4.06)
Peltophorum pterocarpum	15.63 (1.94)	22.19 (2.07)	67.75 (2.75)	49.00 (1.78)
Sandoricum koetjape	71.09 (11.19)		68.14 (14.97)	-
Symplocos macrophylla		0	-	0
Terminalia citrina		36.88 (2.63)		72.00 (3.72)
Vitex pinnata	45.63 (1.94)	38.13 (3.13)	65.75 (3.04)	67.50 (1.19)

For early-sown seeds at both sites and late sown at KB, the mean percentage germination in the field was not significantly different to that obtained in the nursery. Only the late sowing trial at NST, the mean percentage germination in the field was significantly lower to the nursery. MLD was no significant difference between different sowing conditions in both sowing times at all sites (Table 5.4).

Table 5.4 Overview germination and MLD of all germinated species in both field and nursery (S.E.)

		KB		NST	
		Field	Nursery	Field	Nursery
Germination (%)	Early	50.66a (2.76)	40.55a (3.03)	57.69a (3.71)	53.24a (4.64)
	Late	23.91a (2.27)	32.79a (4.78)	30.07a (2.45)	51.44b (4.68)
MLD (days)	Early	31.11a (2.16)	20.40a (5.34)	65.64a (5.25)	65.28a (22.97)
	Late	36.49a (1.84)	47.33a (13.22)	64.86a (7.15)	33.60a (6.04)

Most seeds were collected during beginning and late rainy season at both sites since sowing time was a questionable factor to be investigated. MLDs seemed not to be longer for the species bore fruits in late rainy season. However some species (e.g. *A. clyperia* and *S. koetjape*) dispersed ripe fruits in the late dry or immediately at the rain start (March – April at Krabi and July at Nakhon Si Thammarat) showed shorter MLD than those did few months later, and also for the species that ripening occur at late rainy season (Figure 5.1).

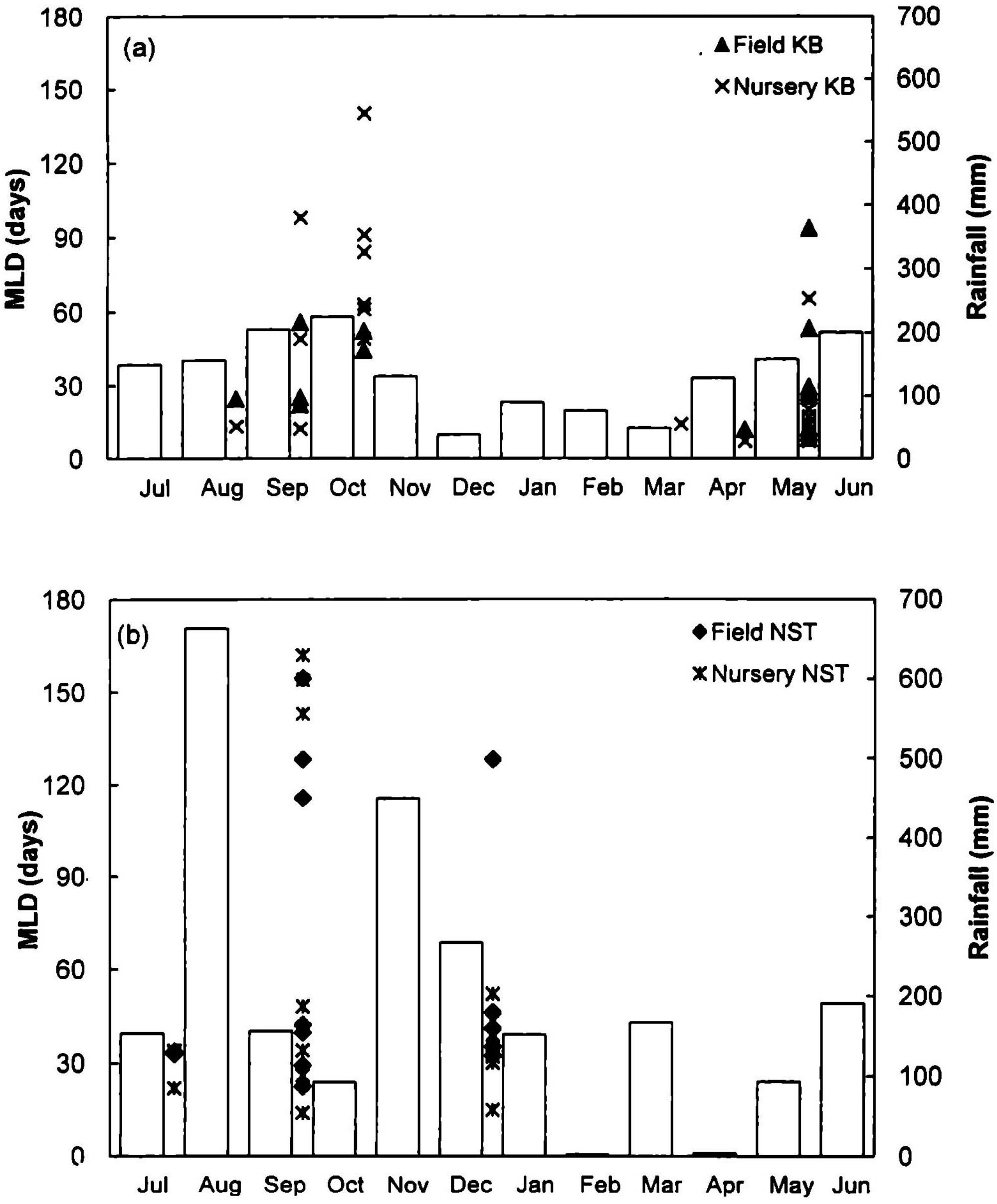

Figure 5.1 MLD of all studied species at (a) KB = Krabi and (b) NST = Nakhon Si Thammarat

5.3.1 Effects of sowing time

Seed availability is a major limitation for direct comparison on the effects of sowing time. Five species were common to both sowing times, however 3 of them (*D. oblonga*, *D. pilosanthera* and *P. pterocarpum*) were excluded from the analyses to allow direct comparisons to be made, because they were stored in refrigerator (10°C) for almost 3 months before used in late sowing. Two species (*M. elliptica* and *V. pinnata*) bore fruits at both sowing times at NST, whereas no species could be collected at both sowing times at KB.

In general, sowing time had a large effect on germination and establishment percentage. The mean percentage germination in early sowing was significantly higher than seeds sown in late sowing for *M. elliptica* but this pattern was not found in *V. pinnata* ($p<0.05$). Establishment percentage was significantly low in late sowing ($p<0.05$). None of late-sown seedlings of *M. elliptica* could survive, after the first dry season. MLD seems to vary between two species, it was significantly shorter in late sowing for *V. pinnata* but longer for *M. elliptica* (Table 5.5).

Direct-seeded seedlings of both species grew better than those grown from the nursery in early sowing while there was no significant difference in late sowing ($p<0.05$). In early sowing, mean RCD and height of direct-seeded seedlings were bigger than nursery-grown seedlings. There was not significantly different growth performance between field and nursery in late sowing ($p<0.05$). However, the crown width varied between species, direct-seeded seedlings of *M. elliptica*, germinated from early sowing, produced significantly larger crowns than those grown from the nursery but there was not significantly different for *V. pinnata* seedlings that germinated from both sowings ($p<0.05$) (Figure 5.2 and 5.3).

Table 5.5 Mean germination, MLD and establishment performance affected by different sowing time for two species that bore fruits available for both sowings (S.E.)

		Early	Late
M. elliptica			
	Germination (%)	69.38a (2.84)	17.81b (4.03)
	MLD (days)	31.94a (0.64)	38.38b (1.82)
	Establishment (%)	14.06 (3.48)	0
V. pinnata			
	Germination (%)	45.62a (3.62)	38.12a (3.92)
	MLD (days)	40.38a (0.77)	30.31b (0.50)
	Establishment (%)	26.25a (3.43)	2.19b (0.91)

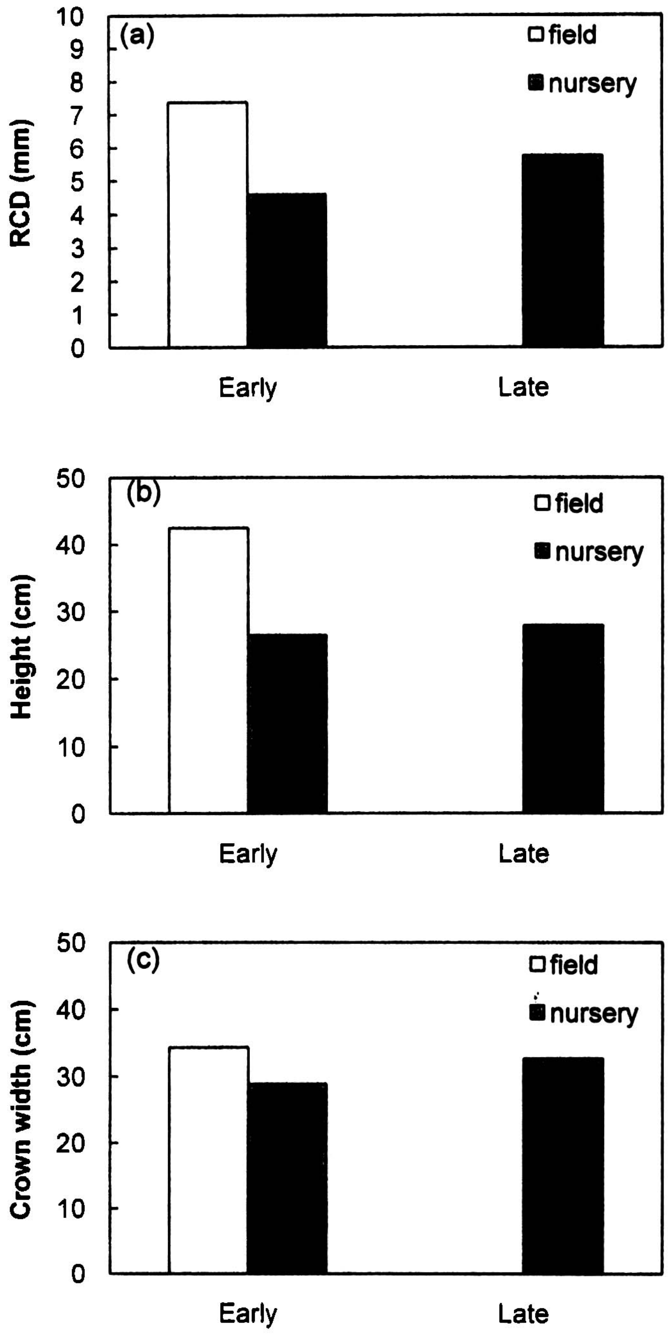

Figure 5.2 Growth performance of *M. elliptica* seedlings germinated from both early and late sowing; mean of (a) RCD, (b) height, and (c) crown width

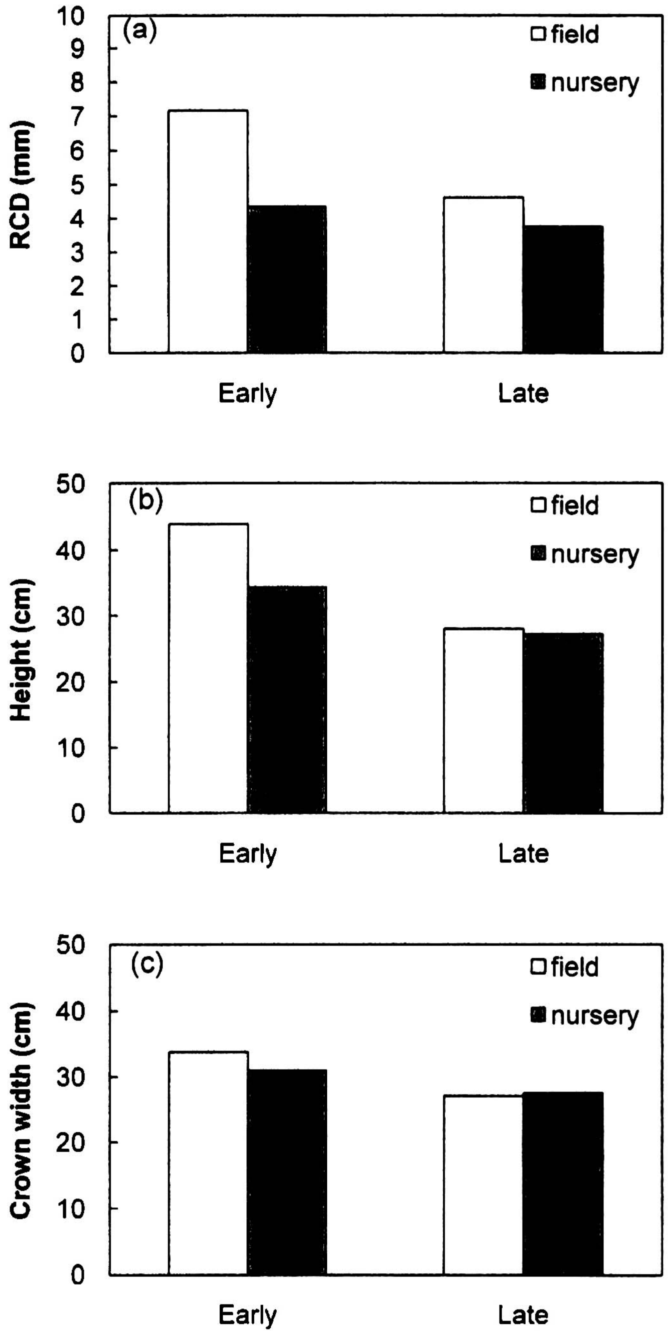

Figure 5.3 Growth performance of *V. pinnata* seedlings germinated from both early and late sowing; mean of (a) RCD, (b) height, and (c) crown width

Similar to *M. elliptica* and *V. pinnata*, the mean percentage germination of random species was not significantly different between field and nursery condition for early sowing ($p<0.05$) (Table 5.4). In contrast, late sowing caused significantly low germination percentage in the field ($p<0.05$) (Table 5.4 and 5.6). MLD was seemed to be two times longer at NST than KB but no significant difference between sowing times and conditions (Table 5.4 and 5.6). Seedling establishment percentage in late sowing was lower in all sites significantly ($p<0.05$) (Table 5.6).

Table 5.6 Mean germination, MLD and establishment affected by different sowing time for groups of random species that bore fruits available for each sowing (S.E.)

		Early	Late
KB			
	Germination (%)	50.66a (1.88)	24.01b (1.44)
	MLD (days)	31.11a (2.16)	36.49a (1.84)
	Establishment (%)	10.78a (1.46)	6.30b (0.90)
NST			
	Germination (%)	59.19a (2.82)	29.06b (2.05)
	MLD (days)	77.44a (6.93)	83.54a (10.60)
	Establishment (%)	16.62a (2.69)	0.83b (0.37)

In general, the direct-seeded seedlings grew better than nursery-grown seedlings for early sowing, but possibly expressed similar growth or even worse of direct seeded than nursery-raised plants for late sowing.

All growth parameters (RCD, height and crown width) of direct-seeded seedlings of KB random species were bigger than those for nursery-grown seedlings, similar to the pattern found in *M. elliptica* and *V. pinnata*, for early sowing. KB direct-seeded seedlings grew significantly better in the field than those grown in the nursery for early sowing and slightly different between late-sown seedlings ($p<0.05$) (Figure 5.4, 5.5 and 5.6)

The mean RCD, height and crown width of the direct-seeded seedlings of NST random species were not significantly different from those of nursery-grown seedlings for early sowing ($p<0.05$). Late-sown direct seeded seedlings at NST had the worst growth performance (Figure 5.4, 5.5 and 5.6).

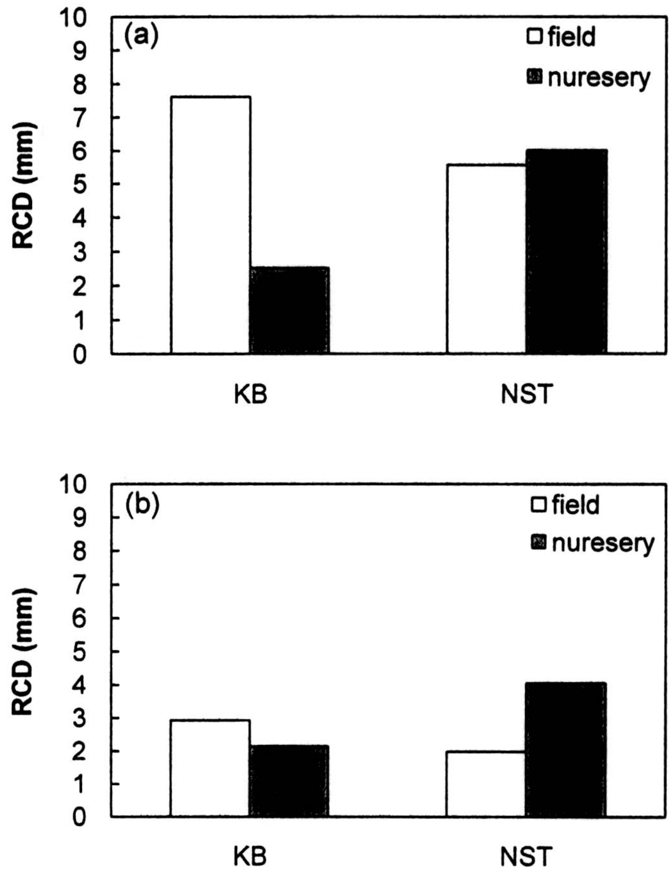

Figure 5.4 Mean RCD of group of random species sown at KB and NST at one year after early sowing; (a) early-sown species and (b) late-sown species

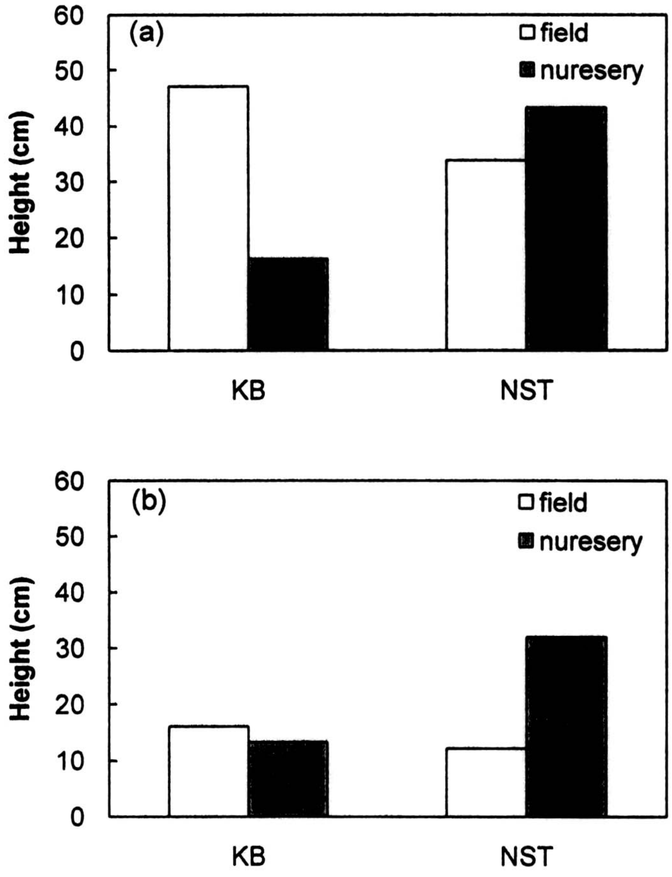

Figure 5.5 Mean height of group of random species sown at KB and NST at one year after early sowing; (a) early-sown species and (b) late-sown species

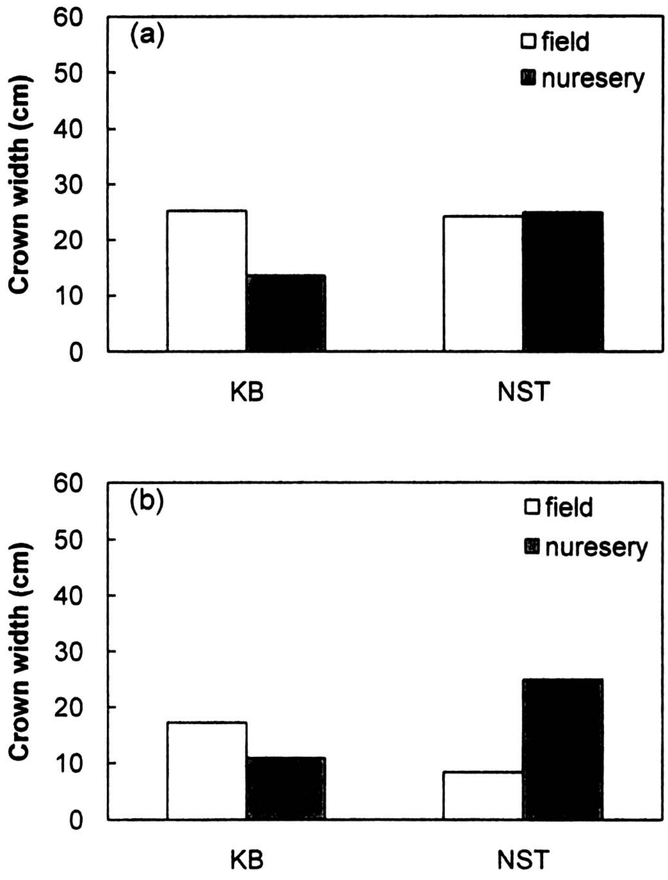

Figure 5.6 Mean crown width of group of random species sown at KB and NST at one year after early sowing; (a) early-sown species and (b) late-sown species

5.3.2 Effects of management regimes

Three species (*D. oblonga*, *D. pilosanthera* and *P. pterocarpum*) were excluded to prevent the effects of seed viability on the results. Only mulching caused significantly smaller mean RCD at NST ($p<0.05$). Seed exclusion and soil nutrient supply had no effect on germination, MLD and growth performance for both sowing times at all sites. Although there was no significant difference of the mean percentage establishment between different nutrient supply, however adding fertiliser seemed to decrease recruitment success, in early sowing at both sites (Table 5.7 and 5.8).

Table 5.7 In early sowing, mean germination, MLD, establishment and growth performance affected by different management regimes for groups of random species that bore fruits available (S.E.)

		Application	KB	NST
Seed exclusion				
	Germination (%)	Yes	53.19a (2.28)	60.83a (2.86)
		No	47.88a (2.50)	55.42a (3.77)
	MLD (days)	Yes	31.59a (3.22)	47.44a (4.21)
		No	30.62a (2.89)	47.44a (4.18)
Mulching				
	Germination (%)	Yes	49.62a (2.52)	58.02a (3.41)
		No	51.44a (2.28)	58.23a (3.33)
	MLD (days)	Yes	34.75a (3.25)	46.38a (4.10)
		No	27.51a (2.81)	48.50a (4.29)
	Establishment (%)	Yes	10.69a (2.13)	18.04a (2.89)
		No	10.88a (2.02)	17.23a (2.96)
	RCD (mm)	Yes	6.09a (0.54)	6.34a (0.41)
		No	9.19b (1.33)	6.18a (0.38)
	Height (cm)	Yes	36.02a (4.93)	37.18a (2.31)
		No	44.01a (4.82)	37.89a (2.84)
	Crown width (cm)	Yes	21.58a (2.00)	27.71a (1.56)
		No	25.20a (2.04)	25.67a (1.63)
Nutrient supply				
	Establishment (%)	Yes	8.75a (1.87)	14.73a (2.38)
		No	12.81a (2.23)	20.54a (3.34)
	RCD (mm)	Yes	7.19a (0.92)	6.25a (0.40)
		No	7.90a (1.08)	6.27a (0.39)
	Height (cm)	Yes	40.76a (5.41)	37.39a (2.50)
		No	39.03a (4.54)	37.65a (2.63)
	Crown width (cm)	Yes	24.43a (2.29)	25.97a (0.89)
		No	22.34a (1.83)	27.39a (0.86)

Table 5.8 In late sowing, mean germination, MLD, establishment and growth performance affected by different management regimes for groups of random species that bore fruits available (S.E.)

		Application	KB	NST
Seed exclusion				
	Germination (%)	Yes	25.00a (2.23)	29.75a (2.13)
		No	22.29a (1.81)	27.50a (1.81)
	MLD (days)	Yes	37.85a (2.84)	63.97a (9.98)
		No	35.13a (2.35)	65.72a (10.35)
Mulching				
	Germination (%)	Yes	22.19a (1.99)	31.50a (2.10)
		No	25.10a (2.06)	25.75a (2.78)
	MLD (days)	Yes	37.13a (2.62)	69.55a (10.57)
		No	35.87a (2.61)	59.78a (9.6)
	Establishment (%)	Yes	6.35a (1.24)	1.25a (0.34)
		No	6.25a (1.33)	0.92a (0.37)
	RCD (mm)	Yes	2.70a (0.18)	2.48a (0.64)
		No	2.61a (0.34)	3.67a (0.88)
	Height (cm)	Yes	15.53a (1.25)	16.43a (3.04)
		No	15.16a (1.86)	23.50a (5.48)
	Crown width (cm)	Yes	15.91a (1.81)	15.93a (4.08)
		No	15.04a (2.27)	18.46a (5.42)
Nutrient supply				
	Establishment (%)	Yes	6.46a (1.26)	0.75a (0.26)
		No	6.14a (1.31)	1.43a (0.44)
	RCD (mm)	Yes	2.80a (0.25)	3.64a (0.89)
		No	2.49a (0.27)	2.31a (0.56)
	Height (cm)	Yes	15.64a (1.34)	21.40a (5.16)
		No	15.03a (1.76)	17.00a (3.11)
	Crown width (cm)	Yes	16.08a (1.90)	21.10a (5.35)
		No	14.83a (2.15)	13.30a (3.32)

5.3.3 Effects of seed storage

Seed storage (refrigerator 10° C for 3 months) decreased germination by about 85% in both nursery and field conditions for *Diospyros* species. Germination of *P. pterocarpum* decreased by 28% in the nursery after 3 months storage but it increased by 42%, in the field. The MLD of *P. pterocarpum* was shorter after storage, while there were no significant differences for both *Diospyros* species ($p<0.05$) (Table 5.9).

Table 5.9 Mean germination percentage and MLD of three species before and after seed storage (S.E.)

	Field condition		Nursery condition	
	Fresh seeds	Stored seeds	Fresh seeds	Stored seeds
D. oblonga				
Establishment (%)	40.62a (2.84)	0.31b (0.31)	-	-
Germination (%)	82.19a (3.16)	7.81b (1.70)	88.25a (1.25)	7.00b (1.35)
MLD (days)	22.06a (1.29)	31.67b (1.26)	26.00a (0)	26.00a (0)
D. pilosanthera				
Establishment (%)	11.25a (2.64)	0.31b (0.31)	-	-
Germination (%)	90.31a (2.30)	23.12b (3.38)	89.75a (1.03)	13.50b (2.33)
MLD (days)	29.81a (0.19)	32.13a (0.94)	26.50a (0.50)	25.00a (0)
P. pterocarpum				
Establishment (%)	5.31a (1.07)	3.75a (0.97)	-	-
Germination (%)	15.62a (2.92)	22.19a (2.04)	67.75a (2.75)	49.00b (1.78)
MLD (days)	117.88a (21.69)	80.31a (15.91)	154.75a (1.80)	93.50b (4.48)

Due to very low recruitment of stored *Diospyros* seeds during the end of 1st dry season, analyses on the effects of mulching and nutrient supply on the percentage establishment and seedling growth performance were not possible.

Predator exclusion did not significantly increase germination of three species for both sowings ($p<0.05$) (Table 5.10, 5.11 and 5.12). Mulching resulted in significantly higher germination of *D. pilosanthera* in early sowing but had no effect on the other two species in both sowings ($p<0.05$) (Table 5.11). Nutrient supply seemed not to be essential for early growth of direct-seeded seedlings for both sowing times. However, the crown width of *P. pterocarpum* seedlings germinated from stored seeds grew significantly larger, when fertilizer was added (Table 5.12).

Table 5.10 Mean germination percentage, MLD, establishment and growth performance in different management regimes of *D. oblonga* for both sowing times (S.E.)

		Application	Early	Late
Seed exclusion				
	Germination (%)	Yes	85.00a (3.66)	8.12a (2.30)
		No	79.38a (5.46)	7.50a (2.11)
	MLD (days)	Yes	22.00a (1.82)	30.83a (1.40)
		No	22.12a (1.96)	32.50a (2.19)
Mulching				
	Germination (%)	Yes	83.75a (3.75)	6.25a (2.45)
		No	80.62a (5.54)	9.38a (1.75)
	MLD (days)	Yes	22.50a (2.04)	28.60a (0.60)
		No	21.62a (1.72)	33.86a (1.71)
	Establishment (%)	Yes	36.88a (3.12)	1.25 (1.25)
		No	44.38a (4.57)	NA
	RCD (mm)	Yes	2.82a (0.21)	1.10
		No	2.76a (0.18)	NA
	Height (cm)	Yes	18.07a (1.33)	11.00
		No	20.40a (1.89)	NA
	Crown width (cm)	Yes	15.40a (1.03)	9.00
		No	15.80a (1.60)	NA
Nutrient supply				
	Establishment (%)	Yes	40.62a (4.48)	NA
		No	40.62a (3.83)	1.25 (1.25)
	RCD (mm)	Yes	3.01a (0.20)	NA
		No	2.57a (0.14)	1.10
	Height (cm)	Yes	20.08a (1.40)	NA
		No	18.39a (1.89)	11.00
	Crown width (cm)	Yes	16.46a (1.06)	NA
		No	14.73a (1.51)	9.00

Table 5.11 Mean germination percentage, MLD, establishment and growth performance in different management regimes of *D. pilosanthera* of both sowing times (S.E.)

		Application	Early	Late
Seed exclusion				
	Germination (%)	Yes	93.12a (1.88)	27.50a (6.05)
		No	87.50a (5.75)	18.75a (3.75)
	MLD (days)	Yes	30.00a (0)	32.00a (0.95)
		No	29.62a (0.38)	32.25a (1.61)
Mulching				
	Germination (%)	Yes	95.62a (0.62)	26.25a (4.98)
		No	85.00b (5.51)	20.00a (5.34)
	MLD (days)	Yes	30.00a (0)	32.12a (0.79)
		No	29.62a (0.38)	32.14a (1.88)
	Establishment (%)	Yes	10.00a (5.77)	0
		No	13.12a (3.77)	NA
	RCD (mm)	Yes	2.97a (0.64)	NA
		No	2.83a (0.44)	1.00
	Height (cm)	Yes	17.09a (2.07)	NA
		No	13.85a (0.67)	10.00
	Crown width (cm)	Yes	10.76a (1.46)	NA
		No	6.94a (1.12)	5.00
Nutrient supply				
	Establishment (%)	Yes	13.75a (5.54)	NA
		No	11.25a (3.87)	0
	RCD (mm)	Yes	2.95a (0.41)	NA
		No	2.80a (0.59)	1.00
	Height (cm)	Yes	16.36a (1.04)	NA
		No	13.50a (1.26)	10.00
	Crown width (cm)	Yes	9.47a (1.62)	NA
		No	6.96a (1.10)	5.00

Table 5.12 Mean germination percentage, MLD, establishment and growth performance in different management regimes of *P. pterocarpum* for both sowing times (S.E.)

		Application	Early	Late
Seed exclusion				
	Germination (%)	Yes	13.75a (3.63)	24.38a (3.71)
		No	17.50a (2.99)	20.00a (3.41)
	MLD (days)	Yes	101.12a (32.40)	56.12a (14.27)
		No	134.62a (29.75)	104.50a (26.73)
Mulching				
	Germination (%)	Yes	12.50a (1.34)	23.75a (3.98)
		No	18.75a (4.30)	20.62a (3.20)
	MLD (days)	Yes	127.38a (29.18)	67.50a (22.06)
		No	108.38a (33.74)	93.12a (23.48)
	Establishment (%)	Yes	6.25a (2.39)	NA
		No	5.00a (1.63)	3.75 (2.39)
	RCD (mm)	Yes	9.48a (2.07)	3.93a (0.73)
		No	14.30a (4.10)	6.96a (1.44)
	Height (cm)	Yes	43.83a (8.17)	17.40a (1.40)
		No	57.30a (19.31)	28.50a (5.91)
	Crown width (cm)	Yes	49.75a (12.80)	22.20a (4.64)
		No	47.30a (9.81)	27.75a (6.23)
Nutrient supply				
	Establishment (%)	Yes	2.50a (1.44)	3.75a (2.39)
		No	6.88a (1.62)	NA
	RCD (mm)	Yes	8.10a (2.29)	6.13a (1.23)
		No	14.65a (3.19)	4.21a (1.20)
	Height (cm)	Yes	33.20a (5.97)	26.20a (5.09)
		No	63.92a (14.91)	17.50a (1.94)
	Crown width (cm)	Yes	33.80a (9.13)	31.30a (3.64)
		No	61.00a (10.28)	16.38b (4.13)

5.4 Discussion

A total of 25 species germinated in the field with highly variable percentage. There was no significant difference in germination percentage between field and nursery conditions for the seeds sown in early rainy season, similar to the study of direct seeding in northern Thailand (Tunjai, 2005), due to high humidity during rainy season. Mean monthly average rainfall exceeded 200 mm at both study sites. In contrast to Hua (1999), this result indicated that low germination is not a barrier for natural regeneration on degraded area in southern Thailand.

However, the results from late sowing varied between study sites, the percentage germination at KB was not significantly different between field and nursery but it was lower in the field at NST. This is possibly because different pattern of rainfall: At KB monthly rainfall exceeded 200 mm for almost 6 months, whereas a highly fluctuating rainfall pattern (300-600 mm) occurred at NST for 3 months during the peak of rainy season. Lower germination in the open area with late sowing was possibly because of reduction or no rainfall at the end of season (Hardwick, 1999).

5.4.1 Effects of sowing time

For the two species, for which seeds could be collected at both sowing times, sowing time had a large effect on germination percentage of *M. elliptica* but not for *V. pinnata*. Low germination was also found in the nursery for late sown *M. elliptica* seeds, whilst there was no difference for *V. pinnata*. Lower seed viability in the late rainy season (see Chapter 2) might be the reason for this effect.

Although different germination percentage was found between different sowing times for groups of random species, however it is possibly due to differently inherent ability of species sown. Nevertheless, the mean percentage germination in the nursery could help to discriminate the effect of different time sowing. Early sowing influenced equal germination between field and nursery condition while late sowing caused lower germination in the field. Early sowing in the beginning of rainy season guarantees sufficient moisture for imbibition and subsequent germination (Khurana & Singh, 2001) and greater moisture protects seeds from desiccation (Morris, 2000).

Low percentage establishment was found for late-sown *V. pinnata* seedlings while no of late-sown *M. elliptica* seedlings survived the 1st dry season. For the group of random species, no *C. soulattri* and *T. citrina* seedlings survived in the field after germination at the end of 1st dry season. Both species were sown in the late rainy season, which had minimum weed competition, since the weeds were cleared just before seeds sown. Clearing vegetation had been mentioned to negatively affect the survival of young seedlings because lacking shelter to protect seedlings from excessive solar radiation and water stress (Hardwick, 1999; Jobidon et al., 1998; Tunjai, 2005). Not only late-sown species, 2 species of early-sown seedlings (*G. merguensis* and *P. longifolia*) also failed to survive at the end of 1st of dry season. Their seedlings were small and sensitive to desiccation, and thus lacked moisture in the subsequent dry season, causing die off (personal observation), similar to the study on degraded areas in central Argentina (Renison et al., 2005).

Early sowing contributed significantly to higher seedling establishment percentage, one year after the first dry period (about 4 times of late sowing). Early-sown direct seeded seedlings should have better developed root systems due to their longer growth period after germination, enabling them to survive during the subsequent dry season. Although direct-seeded seedlings were faced with more intense weed competition from early sowing (Doust et al., 2008) but higher frequency of weed clearing might overcome this constraint, resulting in higher establishment rates. However, this study was not designed to manipulate weed growth and its effect on seedling recruitment.

Sowing seeds in early rainy season maximizes the time for established seedlings to grow (Vieira & Scariot, 2006). *M. elliptica*, *V. pinnata* and KB random species, all achieved higher growth parameters for early sown direct seeded plants, compared with those of nursery-grown seedlings. Sufficient moisture in the early rainy season enabled seedlings to grow better root systems (Fenner & Thompson, 2005) and thus caused better shoot structure in the field. This result was comparable to a study in Hawaii, which reported greater biomass in watered plots (Cabin et al., 2002) which resulted in larger crowns and taller seedlings. Although nursery-grown seedlings received regular watering, they showed smaller size than direct-seeded seedlings, one reason might be the limited space for growing. The effects of container on seedling growth and morphology were found in the study of Close et al. (2005).

In contrast, at NST, all measured growth parameters of direct-seeded plants were not significantly different from those of the nursery-grown seedlings for early sowing, and they were even smaller if grown from late sowing. Fast growing species at NST (e.g. *S. koetjape*) were less tolerant of harsh conditions and most of them eventually died after the 1st dry season in the field, whereas those were grown in the nursery survived. This caused lower mean of measured growth parameters in the field than it should be since this entire fast-growing species died, but they survived in the nursery.

At KB, there were no significant differences in measured growth parameters between field and nursery grown plants from late sowing but at NST they were. In contrast to Doust et al. (2008) less weed competition from late sowing did not allow seedlings to grow better than those grown from early sowing.

5.4.2 Effects of management regime

The assertion that mulching retains soil moisture (Khurana & Singh, 2001) and increases germination (Ammer et al., 2002) was not supported by this study. (Woods & Elliott, 2004) also reported that mulching had little influence on improving germination rate. Many studies have emphasized seed desiccation as a major limitation for the use of direct seeding for forest restoration on degraded area (Doust et al., 2006; Garcia-Orth & Martínez-Ramos, 2008; Woods & Elliott, 2004) but as mentioned earlier, high monthly rainfall in southern Thailand during rainy season could overcome this limitation.

Mulching can suppress weed growth at the base of seedlings (Doust et al., 2006; Laliberte et al., 2007; Snell & Brooks, 1997) and contribute to higher establishment. Unexpectedly, mulching had no effect on establishment of direct-seeded seedlings at the early stage. Mulching had little effect on early growth of seedlings planted on degraded rain forest soils in Malaysia (Nussbaum et al., 1995) while it reduced mean RCD of early-sown seedlings at KB, possibly because there was increased acidic condition from humic acid, when mulched with cut vegetations (Nussbaum et al., 1995), and with higher degree of compaction (Woodward, 1996).

This probably resulted from extensive gleying, typical of the anaerobic conditions waterlogged soils, similar to the result from planted seedlings in the dug soil in Sabah (Nussbaum et al., 1995). The study on type of mulched material and thickness of mulched layer might be further investigated to determine its possible benefit on the establishment success.

Adding nutrients to young seedlings decreased establishment percentage at the end of 1st dry season. Lower soil water potential, as fertility increased (Walker et al., 2004) might cause seedling death because of wilting. This result was in contrast to Zanini and Ganade (2005) who reported that soil fertility did not influence seedling establishment in Brazil. Lack of positive response to fertilization has also been shown for. seedlings of tropical trees establishing in old fields of Central Amazonia where soils are extremely poor (Ganade & Brown, 2002).

Fertilizer application did not affect growth of direct-seeded seedlings at the end of the first dry season. In contrast, Nussbaum et al. (1995) reported that adding nutrients resulted in a dramatic improvement in height, basal diameter and dry weight increments of 4 indigenous species, at 6 months after planting in Malaysia. Tree species require different type and amount of essential nutrients for their growth in various habitats (Van Breugel et al., 2010) and it is possible that the low rates of additional fertilizer used did not exceed loses due to leaching, denitrification and immobilization, and hence available nutrients did not meet plant requirements.

Seed predation had been reported to be a major factor in causing failure of seedling recruitment on degraded area (Hau, 1997), however predator exclusion had no effect on germination in this study. From personal observation, insects were the major seed predators in the study sites, and therefore they had less harmful to the seeds which most were intermediate size with oval or round shape (see Chapter 4).

5.4.3 Effects of seed storage

Three month storage in refrigerator (10° C) caused significantly lower germination percentage in the nursery of all tested species. Harsh conditions in the field resulted in lower germination compared to the ideal conditions in the nursery. However, different sowing times had no effect on germination and recruitment of *P. pterocarpum* seedlings at the end of 1st dry season. Storability or storage potential refers to the inert ability of species to maintain viability for a certain period under ideal conditions, i.e. dry and cool (Schmidt, 2007), this ability is required for direct seeding candidates if there is a timely delay from collection until practical sowing (Tunjai, 2005). Efficient seed storage under ideal conditions can be costly (Bonner, 1990), whilst direct seeding should be a low-cost technique for restoration (Cole et al., 2011; Doust et al., 2006; Woods & Elliott, 2004). Nevertheless, several authors have reported that simple storage conditions can maintain seed viability of some legume species with hard seed coats (Cervantes et al., 1996) (e.g. *P. pterocarpum*) and that contributed to equivalent establishment success. Moreover, *P. pterocarpum* seedlings, germinated from stored seeds, developed significantly broader crowns if additional nutrients were supplied. Additional fertilizer did not contribute to better growth if seedlings experienced sufficient moisture since germinated from early sowing, but it could enhance canopy growth if there was no sufficient moisture like in the study of Van Breugel et al. (2010), to increase probability to survive before subsequent rainy season. Refrigeration is not applicable for *Diospyros* seeds, which showed an almost 85% germination decrease after 3 months storage.

Four species; *A. montanum*, *Aporosa* sp., *F. fragrans* and *H. irya* failed to germinate in the field, but germinated in the nursery, thus seed viability was not a barrier for them. *F. fragrans* and *H. irya* are climax species (personal observation). Light might inhibit their germination during unfavourable conditions for seedling establishment. The ability to detect different aspects of the light environment enables seeds to have at least some control over where and when germination takes place (Fenner & Thompson, 2005). Full sunlight in the field might create an unfavourable microclimate for germination, and possibly contribute to this failure. High light intensity can inhibit seed germination and it has been demonstrated in a number of species (Pons, 2000). Low germination in the nursery might be caused by low seed viability of *A. montanum* and *Aporosa* sp. In addition, harsh conditions in the field and limited rainfall during late sowing possibly caused no germination of these two species.

No *S. macrophylla* seeds germinated in both sowing conditions. This is possibly because of an unsuitable time of seed collection, resulting in unripe or non-viable rotten seeds being collected. Although seed maturity was tested by cutting (only seeds with firm and hard embryo were collected), however other criteria should be considered to affirm seed maturity such as softening of fruit or loosening of fruit pulp (Schmidt, 2007). However there is some species with tiny seeds (e.g. *A. macrophylla*) that expressed difficulty to test maturity by cutting the seeds, in this case, precise phenological data might help to point out the peak of fruit ripening which should be the best time to collect good seed quality.

MLD was not affected by sowing conditions due to likely similar environment (humidity and temperature). As mentioned earlier, rainfall in southern Thailand is high (>1800 mm annually) and this was possibly caused high humidity in the field in similar level as in the nursery where watering was applied regularly. In general, MLD was not affected by sowing time, mulching or seed exclusion. Due to various tested species were mixed among different functional traits (pioneer, climax, etc.) and seed types (orthodox and/or recalcitrant) in each sowing time, thus they might express varied period of dormancy similarly and this is why the difference could not be detected. In this study, mulching with cut vegetations and protecting the seeds with mosquito net did not alter buried seeds (e.g. light intensity and soil moisture) which was possibly affected their dormancy.

Dormancy is determined by genetics with a substantial environmental influence (Finch-Savage & Leubner-Metzger, 2006). Many species have developed this regulatory mechanism to avoid germination under conditions where seedling survival is likely to be low (Schmidt, 2007). A study of seed dispersal and germination of tree species in northern Thailand found that most seeds collected in the late dry and early rainy seasons germinated rapidly (MLDs < 71 days) (FORRU, 2006b), similar to my study in the south, the mean MLDs of species that seeds be collected during the early rainy season were short (about 45 days), they were referred as the 'rapid-rainy group'. However, species that dispersed their seeds late in the rainy season were not in the 'delayed-rainy group'; they showed similar MLDs to those species which dispersed seeds early rainy season, possibly due to adequate moisture and appropriate temperature could trigger germination throughout rainy season in southern Thailand. Dry season may shape unfavourable condition for seeds to germinate, and prolong dormancy, however there was another distinct group, the 'rapid-dry group', which dispersed their seeds in the early dry season and germinated rapidly in the same season. Nevertheless, to argue this theory, more seed collection during dry season will be further needed.

In conclusion, to achieve higher success with direct seeding to restore degraded areas in southern Thailand, sowing seeds in the early of rainy season is the most essential point to keep in mind, because it can increase germination, establishment rate, and better seedling growth performance. Mulching has no affected on investigated factors. Moreover, it reduced mean RCD of seedlings in the site with higher degree of soil compaction. However, it should be considered in further studies particularly where humidity is low, and types of mulch would be necessary to be investigated. Seed predator exclusion had no benefit, if insects are a major predator. This study failed to draw a conclusion about its effect on seed removal. Simply storing seeds in a refrigerator could maintain viability of legume species seeds with hard seed coat for at least 3 months, without considerable loss in viability. Competition with surrounding vegetation is another barrier for succession on abandoned areas, weeding is therefore necessary during fast growing season of weeds, 2 or 3 times in 6 to 8 weeks interval is recommended according the amount of rainfall on each coast. Finally, adding fertilizer does not appear to be necessary during the 1st year after sowing, which can help to keep down the costs of direct seeding.

Chapter 6

Comparing field performance direct seeded and nursery-grown trees

6.1 Introduction

Planting trees is probably the most intensive of forest restoration techniques. It has been used to facilitate forest recovery in abandoned agricultural lands, mining sites and forest gaps (Blakesley et al., 2002; Martinez-Garza et al., 2005; Mine Rehabilitattion Working Group, 2006; Zahawi & Holl, 2009). Many studies have report success with seedling survival rates higher than 80% and substantial forest regeneration beneath certain species (Carpenter et al., 2004; Guariguata et al., 1995; Lamb, 1998).

Two broad approaches have been tested for forest restoration; one approach is to use a small number of fast-growing tree species to create crown cover, which facilitate colonization of the site by a wide range of species from nearby forest. Another approach uses a much greater number of species, representative of more mature successional stages and bypasses the natural regeneration sequence (Cole et al., 2011; Lamb et al., 2005). This approach allows key species to be targeted but it is costly (Erskine, 2002) and sufficient ecological knowledge is a prerequisite to plan seed collection and germinate large numbers of seedlings from a wide variety of species (Engel & Parrotta, 2001; Lamb et al., 2005).

Planting nursery-raised tree seedlings is the most labour- and capital-intensive method of forest restoration; including seed collection, raising seedlings in a nursery, planting and maintenance before planted saplings can establish and become independent (Hardwick et al., 2000). However, planting mixed stands of native hardwoods has been applied broadly; for example, the study of Leopold et al. (2001) reported that when 41 native species were planted in 145 ha of abandoned pastureland in southwestern Costa Rica, pioneer species grew as rapidly as 3.1 m yr^{-1} in height and exceeded 10 cm dbh in 5 years. Among a variety of reforestation methods in eastern Australia, diverse restoration plantings resulted in more complex forest, with a high density of woody stems, a relatively closed crown and shrubby understorey, however they are likely to vary considerably in their value as habitat for rainforest biota (Kanowski et al., 2003).

Moreover, biodiversity recovery has been catalyzed by planting framework tree species, with crown closure achieved 3 years after planting 20-30 framework tree species. Within 6 years, plots were colonized by 61 recruit tree species and bird species richness increased from 30 to 88 (Elliott et al., 2007). It has been proposed that plantations should be established with a high-diversity of native species, in order to create biologically viable restored forests, and to assist long-term biodiversity persistence at the landscape scale (Rodrigues et al., 2010).

In addition to slowing deforestation and forest degradation, it is important to highlight the key role of ecological restoration for biodiversity conservation (Chazdon, 2008), particularly techniques that can be adopted on a large scale (Rodrigues et al., 2009) and which are cost-effective. Direct seeding seems to be an alternative to tree planting as a way to accelerate succession on degraded areas with a minimal cost. The advantages of direct seeding are its low cost (Cole et al., 2011; Doust et al., 2006; Engel & Parrotta, 2001; Lamb & Gilmour, 2003), whilst establishing trees rapidly, yet in a more natural way (Engel & Parrotta, 2001). However, are may be several potential disadvantages to the technique, e.g. due to low germination and survival (Engel & Parrotta, 2001), susceptibility to seed predation (Hau, 1997; Woods & Elliott, 2004) and poor weather conditions (Evans, 1982). On the other hand, direct seeding for species whose seeds are readily available and amenable to this method of establishment, could outweigh its disadvantages and offer a more economical means for reestablishing forest cover over large areas of degraded lands (Applegate et al., 1993; Thompson, 1992).

Studies on direct seeding have concentrated on seed preparation (Sun et al., 1995; Woods & Elliott, 2004), sowing treatments (Doust et al., 2006), sowing time (Doust et al., 2008), soil conditions and weed competition (Balandier et al., 2009). A more systematic screening of potential species and their response to direct seeding under field conditions (Doust et al., 2008; Engel & Parrotta, 2001) is required.

Species choice is critical to the success of direct seeding. Doust et al. (2008) mentioned that the most promising species should at least have one of these characteristics, large seed size (>5 g) and large seedling size after germination, high seed viability, deep root extension, high growth rate potential, etc., although results are likely to vary depending on sowing conditions.

In the tropics, direct seeding for forest restoration has not been widely applied beyond the experimental scale. However, in South America, in a forest restoration program after bauxite mining in Brazil, 21% of species tested by direct seeding was suitable with survival rates ≥ 75% and the proportion of total basal area was slightly higher that of the mixed native species planting (Parrotta & Knowles, 1999, 2001). Similarly, of the five species tested, two legume species planted by direct seeding in a restoring moist forest on abandoned agricultural lands project in southeastern Brazil, showed high germination, seedling survival, and early growth rates, averaging 4.1 – 4.6 cm stem diameter and 1.5 – 1.7 m height growth during the first 2 years after sowing (Parrotta & Knowles, 2001).

Löf *et al.* (2004) compared between direct-seeded and nursery-grown plants in Denmark and Sweden. Transplanted seedlings of beech, oak and wild cherry grew significantly higher than plants derived from direct sowing. Similarly Stanturf et al. (2009) noted that planted _Quercus_ trees grew significantly larger than direct seeded ones in the first few years after establishment.

On the other hand, the establishment of pioneer rainforest tree species, such as *Acacia aulacocarpa*, *Alphitonia petriei* and *Omalanthus populifolius* in northern Queensland by direct seeding, accelerated regeneration of secondary rainforest species in terms of numbers of regenerating species, but there was no significant difference compared with tree planting. In addition, planted and direct seeded trees had similar growth rates (Snell & Brooks, 1997). However, these results were not a fair comparison, since the direct seeded plants had less time for growth and therefore they could not grow taller than transplanted seedlings, which had already had 1-2 years of growth in the nursery. Very few direct comparisons have been made between planting and direct seeding that used the same seed batches. In my previous study

(Tunjai, 2005) in northern Thailand, seeds from the same batch were sown in both field and in the nursery at the same time. Then, nursery-grown plants were transplanted into the field one year after sowing. Direct-seeded seedlings of *Gmelina arborea*, *Melia toosendan* and *Prunus cerasoides* had significant higher survival rates, and developed larger mean of root collar diameter, height and crown width, than nursery-raised seedlings by the second year after sowing.

Evaluation of costs associated with plantation establishment and aftercare is required to determine whether direct seeding is a cost-effective tool for forest restoration. Direct seeding could potentially result in considerable reductions in the costs of forest restoration, nursery-grown plants since the cost of a tree nursery is eliminated and the costs of transport and casual labour should be lower (Cole et al., 2011; Engel & Parrotta, 2001; Sun et al., 1995; Thompson, 1992; Tunjai, 2005). There have been few direct cost comparisons between direct seeding and conventional restoration. However in my previous study (Tunjai, 2005) and that of Cole et al. (2011) demonstrated restoration costs might be reduced by 10-50%, using direct seeding compared to nursery-grown plants. However, this cost evaluation has not been related to the results gained from direct seeding method, in terms of growth performance or seedling density compared to planting. To propose direct seeding as the alternatively sufficient tool for forest restoration, one of the aims of this study was to test if direct it really is more cost-effective, and could contribute to better tree performance, compared with those raised in the nursery.

6.2 Materials and methods

6.2.1 Experimental design

To compare field performance between nursery-raised trees and those established by direct seeding, an experiment was set up using nursery raised trees and direct seeded trees from the experiment described in chapter 4. Seeds of 10 species at most were sown at each sowing time, each species in each sub-plot (2 m x 4 m). Ten sub-plots per one experimental plot (4 m x 20 m), 4 experimental plots per one block (4 m x 8 m), which half of them had been assigned to nutrient supply treatment. A total 4 blocks was assigned to early sowing in the beginning of rainy season and other

4 blocks were assigned to late sowing in late rainy season. Each nursery-raised tree was planted next to a direct-seeded tree randomly at the same number per species per each experimental plot, early-sown species were transplanted only in early sowing blocks, similarly late-sown species were only transplanted in late sowing blocks.

Seeds were sown in the field and nursery at the same time in each sowing event each site, 19 species was tested in early sowing (10 species at KB and 9 species at NST), 16 species in late sowing (10 species at KB and 10 species at NST with 4 species available at both sites), and 5 species overlapping between both sowing times (Table 5.1). At one year after early sowing in each site, the nursery-grown plants were transplanted into the field, randomly next to the surviving of direct-seeded tree seedlings, with similar number within each experimental plot, about 50 cm apart, similar interval when seeds were sown. At KB, the nursery-grown plants of 20 species were transplanted next to the 15 surviving species of direct-seeded seedlings. And at NST, 12 species of the nursery-grown plants were transplanted next to the 10 surviving species of direct-seeded trees. Nursery-grown seedlings produced from early-sown seed batch were transplanted only in early sowing blocks, similar to late-sown seedlings.

6.2.2 Data collection and statistical analysis

Root collar diameter (RCD), height and crown were measured for all surviving trees crown 2 weeks after transplantation and at the end of the 1st rainy season after planting. Mean relative growth rates (MRGR) were calculated using this equation:

$$\text{MRGR} = \frac{\ln G2 - \ln G1}{t2 - t1}$$

where ln G1 and ln G2 are the natural logs of growth performance measurements at the beginning (t1) and end (t2) of the sampling period (South, 1995). About 4 to 6 weeks after transplanting, hand weeding was done with additional fertiliser following the treatments, three times during wet season. Weeding at the NST site was reduced from three to two times due to continuing heavy rains in the area.

Thereafter, eight trees of each of three representative species from both the nursery and the field and for both sowing times were randomly harvested to measure biomass at the end of the 1st rainy season after planting. *A. dadah*, *G. hombroniana* and *P. obovatum* were representative species for early sowing in KB while *P. pterocarpum*, *S. siamensis* and *V. pinnata* were collected from late sowing blocks. At NST, there was very few seedlings survived from late sowing, only one species was harvested (i.e. *P. pterocarpum*) while five species are representative for early sowing, *D. oblonga*, *C. atropurpurea*, *V. pinnata*, *P. pterocarpum* and *M. elliptica*. Root length, and root/shoot ratio were calculated using the following equation:

$$\text{Root/shoot ratio} = \frac{\text{Dry weight for roots}}{\text{Dry weight for top of plant}}$$

Operational costs and labour requirements for activities related to establishment and maintenance were recorded throughout the study period for both direct-seeded and nursery-grown plants. These included all materials, machinery and labour costs associated with production of planting materials, site preparation, plantation establishment and maintenance. These data was used to calculate the initial plantation costs at each site for comparison.

A Generalised Linear Model (GLM) was used to identify the impact of location, seedling source and soil nutrient supply on growth data (RCD, height, crown width and MRGR) and root/shoot ratio since heterogeneity and non-normality were detected. Gamma errors were adopted, when the variance increased strongly with the mean while Poisson errors were employed, when variance increased linearly with the mean. GLM was also used to analyse the survival percentage (with binomial error) and no. of established seedlings (with poisson error) between direct-seeded and nursery-grown plants at the end of 1st rainy season after transplanting. All statistical analyses were performed using the statistical software R 2.11.1 (R Development Core Team, 2010).

6.3 Results

Twenty 20 direct-seeded species and 26 nursery-grown species survived to the end of 2nd rainy season after sowing. No direct-seeded seedlings of the five following species survived to the end of 2nd rainy season after sowing: *C. glabrum*, *C. soulattri*, *G. merguensis*, *P. longifolia* and *T. citrine* (3 out of 5 species germinated from late sowing). Survival of all species exceeded 40% by the onset of the first dry season after transplantation except *G. merguensis* (Table 6.1).

In general, the mean percentage survival of direct-seeded seedlings was significantly higher than that of nursery-raised plants at the end of 1st rainy season after transplanting ($p<0.05$) (Figure 6.1a). However, there was a significant interaction between sowing time and source of seedlings ($p<0.05$). The survival percentage of direct-seeded seedlings, grown from early sowing, was generally higher than that of nursery-grown plants, whilst there was no significant difference in survival percentage of nursery-raised trees compared with direct seeded trees from late sowing (Figure 6.1b).

Table 6.1 Mean percentage of survival at the end of 1st rainy season after transplanting (S.E.)

Species	Direct-seeded plants	Nursery-grown plants
Alstonia macrophylla Wall. ex G. Don	83.33 (11.78)	87.22 (4.20)
Archidendron clyperia (Jack) Niels.	85.42 (8.59)	42.10 (6.77)
Artocarpus dadah Miq.	80.02 (5.66)	62.06 (7.64)
Callerya atropurpurea (Wall.) Schot	88.40 (2.48)	82.06 (3.80)
Calophyllum soulattri Burm. f.	0	44.52 (7.20)
Canthium glabrum Bl.	0	94.05 (2.92)
Cinnamomum iners Reinw. ex Bl.	75.19 (10.12)	67.52 (12.31)
Diospyros oblonga Wall. ex G. Don	93.34 (3.19)	86.01 (3.63)
Diospyros pilosanthera Blanco	95.56 (4.44)	78.11 (5.90)
Elaeocarpus stipularis Bl.	75.00 (25)	100.00
Garcinia cowa Roxb.	100.00	90.18 (3.98)
Garcinia hombroniana Pierre	87.35 (7.24)	65.13 (9.94)
Garcinia merguensis Wight	0	25.00 [a]
Horsfieldia irya (Gaertn.) Warb.	NG [b]	57.46 (8.83)
Lepisanthes rubiginosa (Roxb.) Leenh.	53.57 (3.57)	54.12 (7.43)
Litsea grandis (Wall. ex Nees) Hk.f.	89.18 (5.28)	55.10 (11.05)
Microcos paniculata L.	88.64 (7.13)	83.67 (9.24)
Morinda elliptica (Hk.f.) Ridl.	97.14 (2.86)	91.89 (4.18)
Pajanelia longifolia (Willd.) K. Sch.	0	52.78 (9.21)
Palaquium obovatum (Griff.) Engl.	83.97 (3.77)	56.46 (9.74)
Peltophorum pterocarpum (DC.) Back. ex K. Hey.	89.32 (4.36)	88.50 (3.22)
Sandoricum koetjape (Burm.f.) Merr.	90.00 (10.00)	89.56 (3.82)
Scolopia spinosa (Roxb.) Warb.	63.89 (13.89)	29.31 (5.16)
Sindora siamensis Teysm. ex Miq.	53.52 (14.36)	46.43 (7.41)
Terminalia citrina (Gaerth.) Rox. Ex	0	81.03 (9.42)
Vitex pinnata L.	85.62 (6.28)	80.60 (5.77)

[a] Only one seedling left by the end of 1st rainy season after transplanting

[b] NG: No germination of *H. irya* in the field

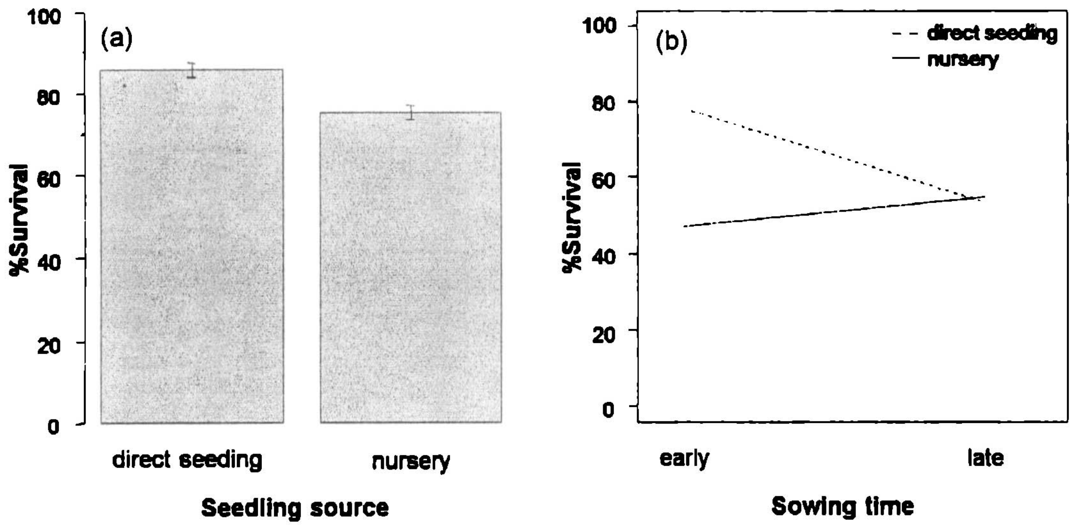

Figure 6.1 Mean percentage of survival at the end of 1st rainy season after transplanting; (a) comparing between direct-seeded and nursery-grown plants and (b) interaction between sowing time and source of seedling

6.3.1 Comparing growth performance

In the first year after seed collection, direct seeded plants of most of the species tested grew significantly larger in the field plots, compared with the plants in the nursery, which were subsequently transplanted into the field. After nursery-raised plants had been transplanted into the field, these differences became even more pronounced during the second wet season of growth.

One year after sowing, all measured growth parameters were significantly higher in direct-seeded than nursery-grown plants at KB ($p<0.05$). At NST, however only RCD was significantly larger at NST 1 year after sowing (not height and crown width) ($p<0.05$) (Table 6.2). A significant interaction between sowing time and seedling source was detected for mean RCD and height at KB ($p<0.05$), whilst no significant interaction was detected at NST. Direct-seeded plants showed larger mean RCD and height than nursery-raised plants at KB if germinated from early sowing while they were not significant difference for late sown plants (Figure 6.2).

At the end of 2nd rainy season after sowing, all measured growth parameters were significantly higher for direct-seeded plants than for nursery-grown ones at both sites ($p<0.05$) (Table 6.2). Again, there was a significant interaction between sowing time and seedling source for mean RCD and crown width ($p<0.05$). Direct-seeded plants, grown from both sowing times showed larger RCD than nursery-grown plants at KB at the end of 2nd wet season after sowing (Figure 6.3a). In contrast, direct-seeded plants had significantly larger RCD and crown width than those grown from the nursery only if they were sown at beginning of wet season at NST ($p<0.05$) (Figure 6.3b and 6.3c).

Table 6.2 Mean of growth performance between direct-seeded and nursery-grown plants at 1 year after sowing (T1) and the end of 2nd rainy season after sowing (T2) (S.E.)

		Direct-seeded plants		Nursery-raised plants	
		T1	T2	T1	T2
RCD (mm)					
	KB	5.47a (0.53)	15.42a (1.36)	2.21b (0.08)	7.66b (0.48)
	NST	5.60a (0.38)	8.94a (0.62)	4.11b (0.15)	7.35b (0.21)
Height (cm)					
	KB	30.07a (3.03)	88.72a (7.23)	13.45b (0.61)	42.77b (3.18)
	NST	31.16a (1.89)	41.32a (2.66)	27.96a (1.41)	36.28b (1.20)
Crown width (cm)					
	KB	20.20a (1.36)	54.24a (4.12)	11.05b (0.45)	32.77b (2.19)
	NST	23.62a (1.52)	29.28a (1.78)	23.43a (0.71)	24.76b (0.74)

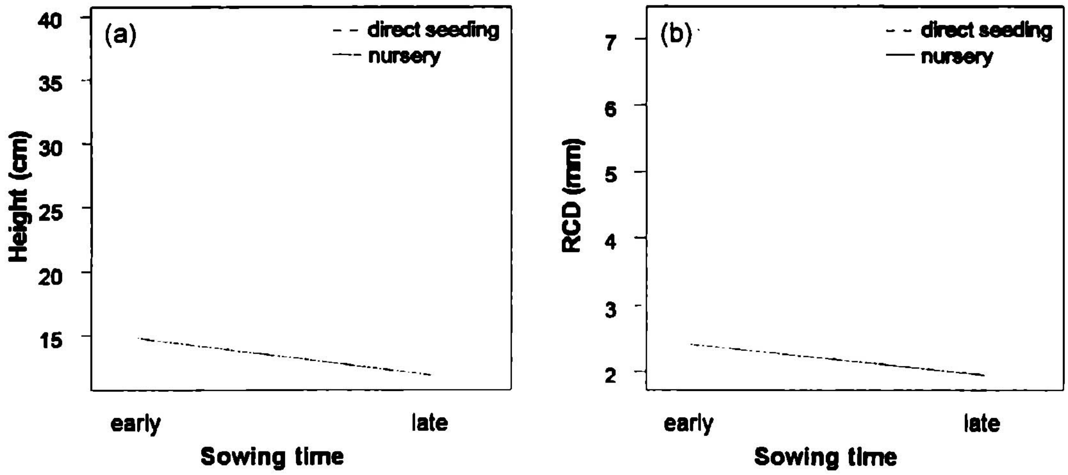

Figure 6.2 Interaction between sowing time and source of seedling on mean of (a) RCD and (b) height at KB at the 1 year after sowing

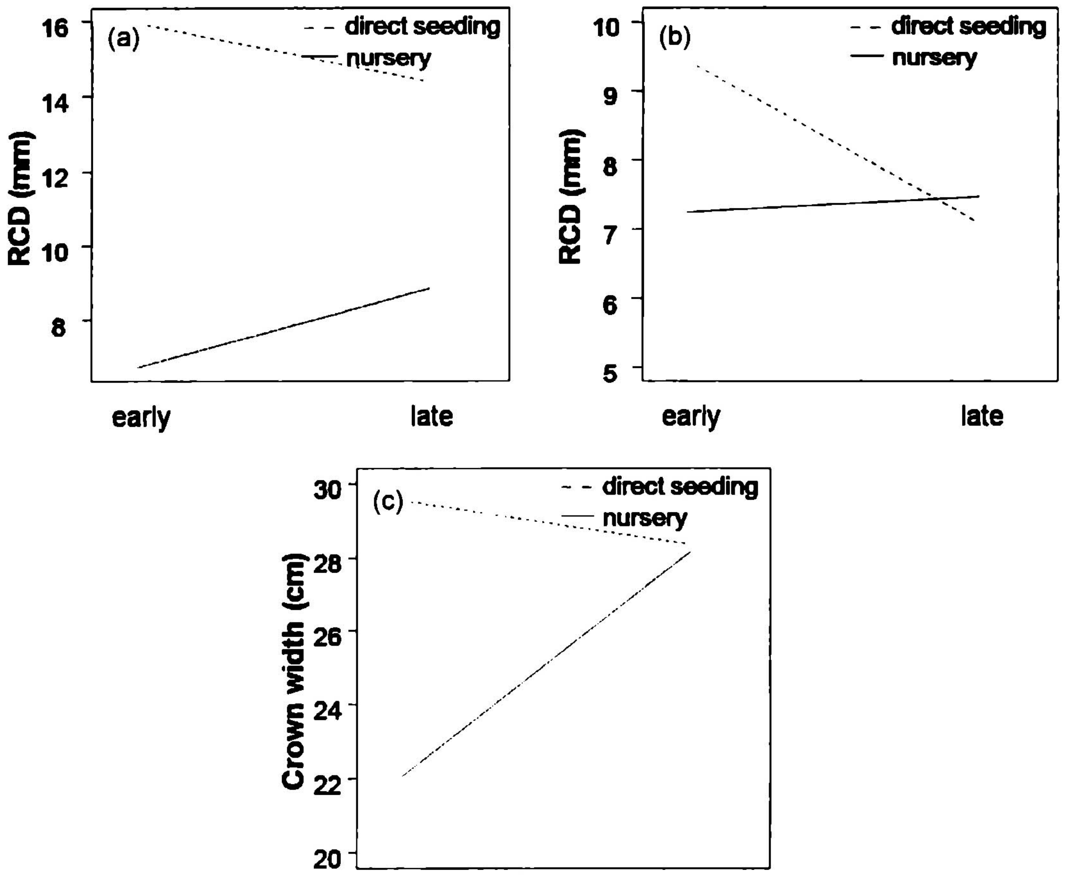

Figure 6.3 Interaction between sowing time and source of seedling on mean RCD of seedlings grown in (a) KB and (b) NST, and (c) mean crown width of seedlings grown at NST, at the end of 2nd rainy season after sowing

There was no significant difference in MRGR between direct-seeded and nursery-grown plants at both sites (Table 6.3). However, there was a significant interaction between sowing time and seedling source (*p*<0.05). Direct-seeded plants grown from late sowing showed higher MRGR in RCD (Figure 6.4a) and crown width (Figure 6.4b) than nursery-grown plants while nursery-grown plants, grown from early sowing, showed higher MRGR in both parameters.

Table 6.3 Mean relative growth rate (MRGR) of direct-seeded and nursery-grown plants at the end of 2nd rainy season after sowing (S.E.)

Species		Direct-seeded plants	Nursery-grown plants
MRGR of RCD			
	KB	1.81a (0.14)	1.98a (0.12)
	NST	1.38a (0.10)	1.54a (0.07)
MRGR of height			
	KB	1.94a (0.12)	1.83a (0.11)
	NST	0.77a (0.05)	0.97a (0.06)
MRGR of crown			
	KB	1.68a (0.12)	1.78a (0.10)
	NST	0.87a (0.06)	0.85a (0.06)

In general, soil nutrient supply contributed significantly to broader tree crowns (*p*<0.05) (Figure 6.5). However, fertiliser had no effect on growth performance, MRGR, dry weight and root/shoot ratio when considered for each site separately (Table 6.4).

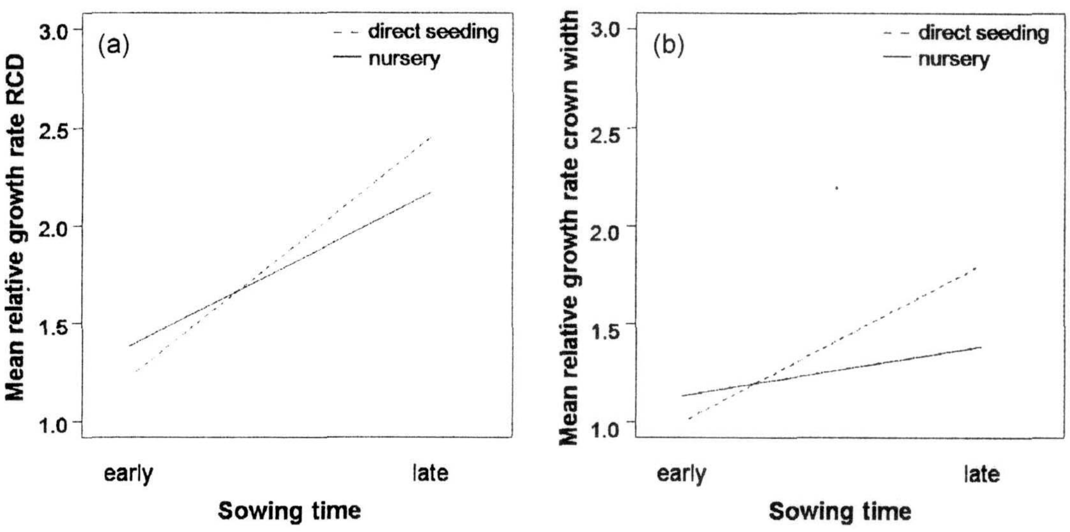

Figure 6.4 Interaction between sowing time and source of seedling on MRGR of (a) RCD and (b) crown width, at the end of 1st rainy season after transplanting

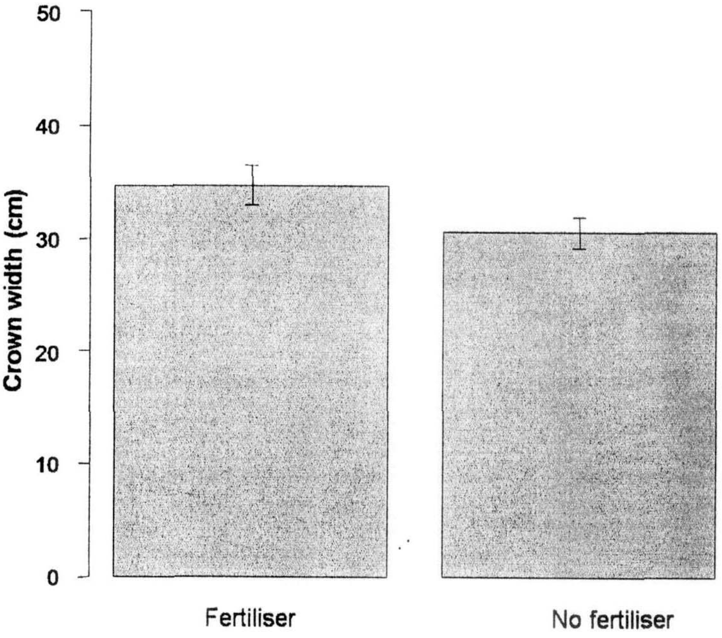

Figure 6.5 Mean crown width between different nutrient supply regimes at the end of 1st rainy season after transplanting

Table 6.4 Mean of growth data, relative growth rate (MRGR) and root/shoot ratio between different nutrient supply regimes at the end of 1st rainy season after transplanting (S.E.)

		Nutrient supply	
		Yes	No
RCD (mm)			
	KB	11.47a (1.08)	9.76a (0.78)
	NST	8.03a (0.34)	7.88a (0.41)
Height (cm)			
	KB	64.16a (5.63)	56.35a (5.11)
	NST	39.11a (1.58)	37.35a (1.93)
Crown width (cm)			
	KB	43.73a (3.51)	38.19a (2.74)
	NST	27.91a (1.06)	25.18a (1.24)
MRGR of RCD			
	KB	2.09a (0.13)	1.75a (0.12)
	NST	1.46a (0.09)	1.50a (0.08)
MRGR of height			
	KB	2.00a (0.13)	1.74a (0.10)
	NST	0.90a (0.07)	0.89a (0.06)
MRGR of crown			
	KB	1.87a (0.11)	1.62a (0.11)
	NST	0.87a (0.06)	0.84a (0.06)
Dry weight (g)			
	KB	66.72a (30.94)	35.28a (12.30)
	NST	19.84a (3.49)	31.83a (10.35)
Root/shoot ratio			
	KB	0.55a (0.16)	0.46a (0.10)
	NST	0.62a (0.07)	0.68a (0.10)

Mean dry weight of direct-seeded plants was significantly higher than that of nursery-grown plants ($p<0.05$) (Figure 6.6a and Table 6.5) but no significant difference in root/shoot ratio was detected between the two plant sources (Table 6.5). However, plants from early sowing had a significantly higher root/shoot ratio than that of late-sown plants ($p<0.05$) (Figure 6.6b).

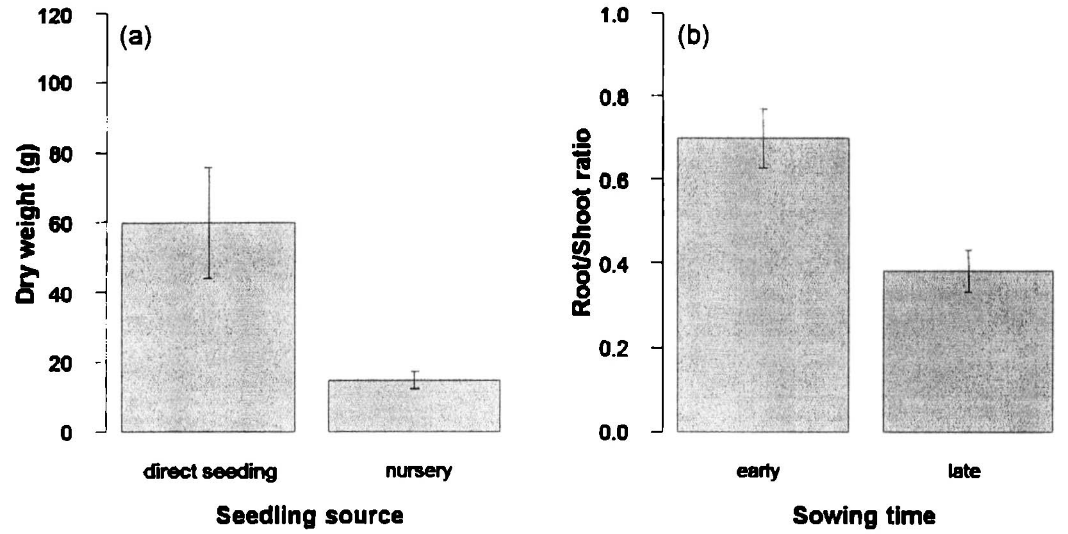

Figure 6.6 Mean dry weight and root/shoot ratio between (a) direct-seeded and nursery-raised plants and (b) early-grown and late-grown seedlings, at the end of 1st rainy season after transplanting

Table 6.5 Mean dry weight and root/shoot ratio between direct-seeded and nursery-raised plants at the end of 1st rainy season after transplanting (S.E.)

		Direct-seeded plant	Nursery-grown plants
Dry weight (g)			
	KB	85.72a (29.33)	12.73b (3.75)
	NST	33.89a (9.47)	16.78b (3.34)
Root/shoot ratio			
	KB	0.42a (0.11)	0.59a (0.14)
	NST	0.58a (0.09)	0.71a (0.07)

6.3.2 Comparing costs and establishment

For direct and fare comparison, only established seedlings from early sowing (see Table 5.1) were investigated here. Establishing trees by direct seeding eliminated nursery and seedling transferring costs and resulting in a reduction in costs of 30%. The details were presented in Table 6.6 and Figure 6.7.

In general, there was no significant difference in the number of direct-seeded and nursery-raised plants surviving at the end of 1st rainy season after transplanting. A total of 448 and 467 seedlings were established by direct seeding and planting respectively, surviving in an area of 0.16 ha, 18 months after early sowing. More than 100 direct seeded plants survived of *C. atropurpurea* and *D. oblonga*, but most other species resulted in only 30-100 established plants by direct-seeding e.g. the 9 species *V. pinnata*, *A. dadah*, *M. paniculata*, *M. elliptica*, *P. obovatum*, *G. hombroniana*, *D. pilosanthera*, *L. grandis* and *C. iners* whilst 6 species had less than 30 individuals surviving after 18 months e.g. *S. koetjape*, *A. clyperia*, *P. pterocarpum*, *S. spinosa*, *L. rubiginosa* and *G. cowa* and no plants survived of 2 species (*G. merguensis* and *P. longifolia*) (Figure 6.8).

In this study, the cost per tree is 33 and 45 baht for direct-seeded and nursery-grown plant calculating from seed collection until 2nd year maintenance in the field. The cost per tree for nursery-grown plant might be more expensive from the standard method (planting 500 trees per rai) because equal number to direct-seeded plant was required, and it turned out to be 650 trees per rai. Apparently, the cost per tree between these two methods seemed to be different although the plastic tubes were used to prevent seeds from moving in direct seeding technique. However, establishing trees by direct seeding could save about 50% if the cost of plastic tubes was removed, and therefore cost per tree will be decreased to be almost half price of nursery-grown plant (25 baht per tree).

Table 6.6 Establishment and maintenance costs of direct seeding and planting through 2 years of study*

Items	Baht/rai [a]		Note
	Nursery-raised plants	Direct-seeded plants	
Establishment cost			
- Nursery			
Seed collection	675.00	900.00	0.23 baht/seed, 9 hrs for 1,000 seeds
Seed preparation	450.00	600.00	0.15 baht/seed, 6 hrs for 1,000 seeds
Germination [b]	267.58	0	*Basket* ; 0.03 baht/seed, 200 seeds/basket, 15 baht/basket, 3 planting seasons/basket *Media* ; 1.17 baht/basket, 200 seeds/basket *Labour* ; 3 hr for 1000 seeds
Potting b	2,403.52	0	*Plastic bag* ; 0.19 baht/bag, 236 bags/kg, 45 baht/kg *Media* ; 0.18 baht/bag *Labour* ; 2.4 baht/bag
Raising	9,991.09	0	*Fertiliser* ; 180 baht/500 seedlings, 3 times/planting season *Watering* ; 1.5 hrs/1,000 seedlings, every 2 days *Maintenance* ; 12 hrs/1,000 seedlings, every month
- Site preparation			
Ploughing	1,500.00	1,500.00	1,500 baht/rai

Table 6.6 (Continued)

Items	Baht/rai [a]		Note
	Nursery-raised plants	Direct-seeded plants	
- Planting/Sowing			
Seedling transferring	520.00	0	0.80 baht/seedling
Planting/seeding	455.00	640.00	*Planting* ; labour 0.40 baht/seedling, apply fertiliser 0.30 baht/seedling *Sowing* ; labour 0.20 baht/seed
Materials	1,196.00	3,600.00	*Planting* ; fertiliser 0.84 baht/seedling, stake 1 baht each *Sowing* ; plastic tube 2.25 baht each, 2 planting seasons/tube
Subtotal	**17,458.19**	**7,240.00**	
Maintenance costs			
- 1st year			*Mechanical weeding* ; averaged 2,000 baht/rai for direct seeded plants in 1st year, 500 baht/ rai for both planting and direct seeding plots in 2nd year
Weeding	0	6,000.00	
Fertiliser	0	0	
- 2nd year			
Weeding	1,500.00	1,500.00	
Fertiliser	2,223.00	0	*Fertiliser* ; averaged 8.4 baht/kg, 0.84 baht/seedling
Subtotal	**3,723.00**	**7,500.00**	
Total costs	**21,181.19**	**14,740.00**	

* During the period of study, manual labour cost average 200 baht per day (8 hr)

[a] 1 hectare = 6.25 rais

[b] Averaged germination was about 50% in the nursery, 40% were potted and 30% were ready for transplanting.

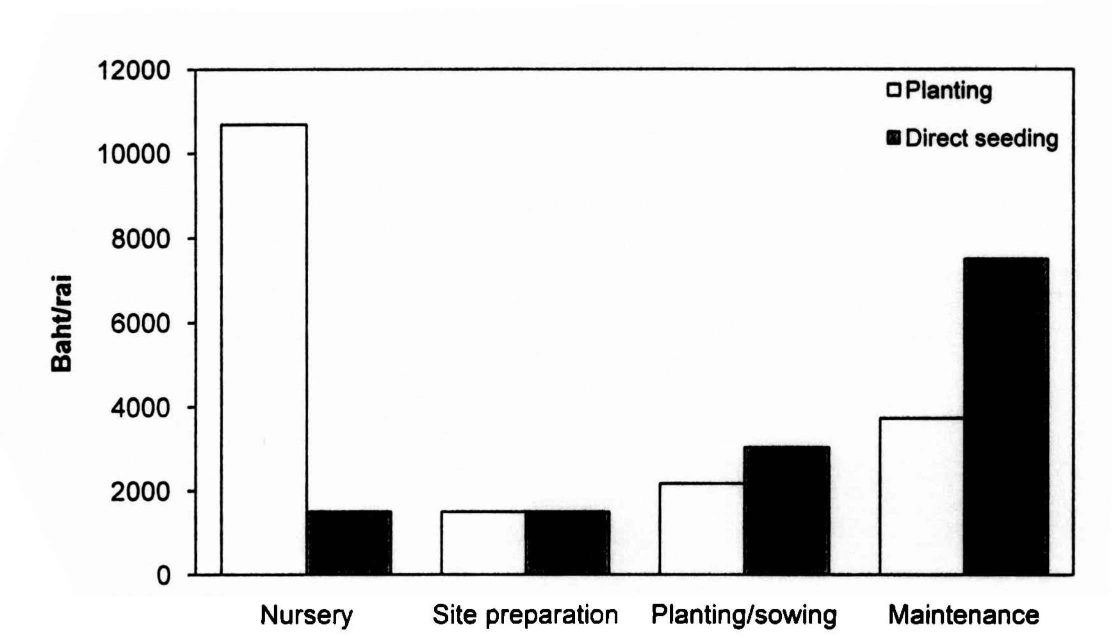

Figure 6.7 Establishment and maintenance costs compared between planting and direct seeding method

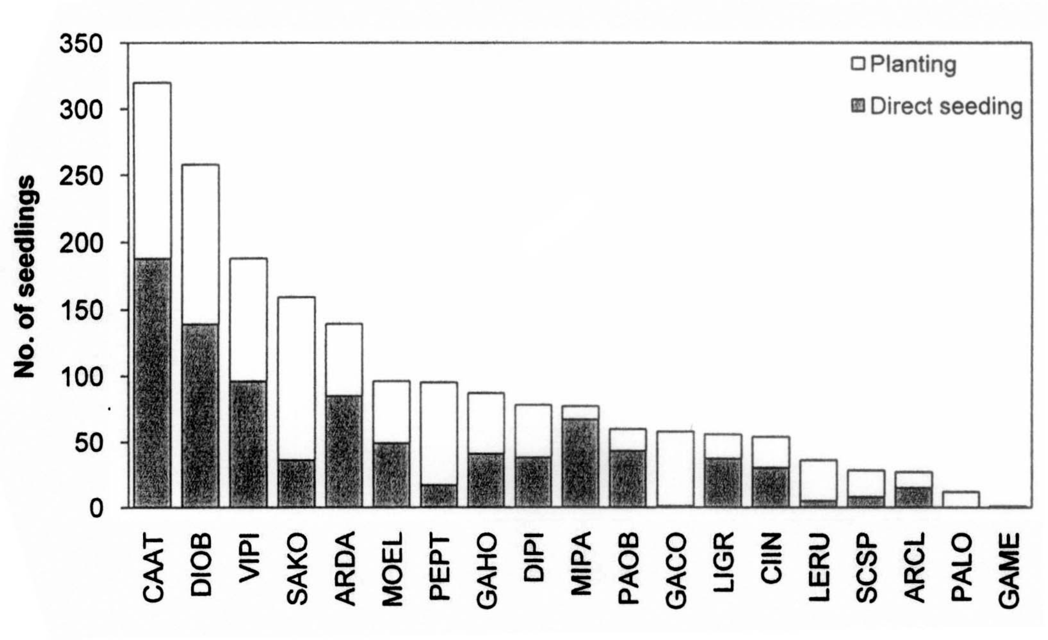

Figure 6.8 No. of established seedlings grown from planting and direct seeding method at the end of 1st rainy season after transplanting (in the area 0.32 ha); ARCL = *A. clyperia*, ARDA = *A. dadah*, CAAT = *C. atropurpurea*, CIIN = *C. iners*, DIOB = *D. oblonga*, DIPI = *D. pilosanthera*, GACO = *G. cowa*, GAHO = *G. hombroniana*, GAME = *G. merguensis*, LERU = *L. rubiginosa*, LIGR = *L. grandis*, MIPA = *M. paniculata*, MOEL = *M. elliptica*, PALO = *P. longifolia*, PAOB = *P. obovatum*, PEPT = *P. pterocarpum*, SAKO = *S. koetjape*, SCSP = *S. spinosa*, and VIPI = *V. pinnata*

6.4 Discussion

No direct seeded plants of *C. soulattri*, *G. merguensis*, *P. longifolia* and *T. citrina* established and survived in the field until the end of the 1st dry season, as previously discussed in Chapter 4. Only one seedling of *C. glabrum* survived until the end of 1st dry season after sowing, probably because the seeds had been sown in late rainy season and thus lacked moisture in the subsequent dry season causing seedling die back (personal observation).

The significantly lower mean survival percentage of nursery-raised plants compared with direct seeded plants at the end of the 2nd rainy season after sowing was probably explained by transplant shock during transferring and handling plants at planting time. Transplantation of nursery-raised plants must be carried out carefully to minimize damage. Nevertheless, FORRU (2006a) reported that seedlings can be damaged by overheating and dehydration during transport to the planting plot and the shoot system may also be further damaged, if the containers are not packed carefully in the vehicle. Damaged seedlings could easily die under severe conditions, which is a symptom of transplant shock (Reitveld, 1989). In contrast, mean survival percentage of direct seeded plants was not different from that of nursery-raised, when sown late in the rainy season. This is because late-germination does not allow the plants to develop suitable deep root systems to enable the plants to find water during the 1st dry season (Doust et al., 2008).

6.4.1 Comparing growth performance

In 1st year before planting, direct seeded plants of most tested species grew significantly larger than nursery-raised plants. More naturally established seedlings by direct seeding (Engel & Parrotta, 2001) would enable better developed root systems than transplanted seedlings which grew in restricted containers (Close et al., 2005). Levels of carbohydrate and nutrient reserve are related to seedling size (Ritchie, 1982) as could be seen from significantly higher mean dry weight of direct-seeded plants and their better growth performance in the field.

Harsher conditions might explain the smaller mean tree heights and crown widths of direct seeded plants in year one at NST. Higher monthly maximum and average temperature, water-logging during wet season and severe drought during dry season at NST might have caused the plants to grow slowly in the field. Lack of moisture is another common factor on degraded areas or fragmented forest that causes high seedling mortality (Fenner & Thompson, 2005). At times, the shoots of seedlings died during dry season at NST and re-sprouted when sufficient moisture had achieved in wet season (personal observation). Re-sprouting is an important persistence strategy for woody species with potentially large consequences for vegetation dynamics, this ability, as well as investments in stem defense and storage reserves, form part of a suite of co-evolved traits that underlies the growth-survival trade-off (Poorter et al., 2010).

At the end of 1st rainy season after transplanting, all measured growth parameters were significantly higher for direct-seeded plants than for nursery-grown plants at both sites. Correspondingly, dry weight of direct-seeded plants was significantly higher than that of nursery-grown plants at both sites. A decreased growth rate of newly planted seedlings, compared to direct seeded plants that more naturally established of the same age, is a symptom of transplant shock (Reitveld, 1989). The transplanted seedlings in harsh condition were stressed as acclimatization occurs over several days or weeks and the stresses negatively affected on photosynthesis. The occurrence of decreased photosynthetic efficiency is termed photo-inhibition and this may arise directly due to sudden increases in irradiance, or indirectly through a stress that limits photosynthesis and induces conditions of excess light absorption, e.g. water-logging or drought (Close et al., 2005).

At KB, mean RCD of direct seeded plants was significantly higher than that of nursery-raised plants at one year and the end of 2nd rainy season after sowing, if germination occurred at the beginning of rainy season, but only at the end of the 2nd rainy season if the seeds were sown late in the rainy season. This is possibly because there was insufficient time to grow during 1st wet season after sowing but longer growing period during 2nd wet season. In contrast, at NST, only direct seeded plants germinated from early sowing had bigger RCD than the nursery-raise plants at end of 2nd rainy season. Harsher conditions were prevalent at NST, and this might have caused slower growing of seedlings in the field. Direct seeded plants from early sowing had enough time for establishing their root system, thus enabling them to grow faster in the 2nd wet season.

Drought-induced stress is the most widely studied and perhaps the most common cause of transplant shock in tree seedlings (Burdett et al., 1984; Burdett et al., 1983; Grossnickle, 1988; Jarvis & Jarvis, 1963). Drought stress following transplanting is further exacerbated by poor acclimatization to the field environment (Rowe, 1964) and caused smaller RCD of transplanted seedlings compared to direct seeded plants. Particularly, if soils are blocky or clumpy and seedlings are not planted carefully, poor root ball-soil contact can occur (Sands, 1984; Wilson & Clark, 1998), and this could cause air gaps to form between potting media and surrounding soil, and prevents moisture and nutrient uptake (Sands, 1984) which resulted in smaller RCD of nursery-raised plants.

Mean relative growth rates (MRGR) have been frequently used to compare growth of seedlings that differ in initial size for two reasons; first to eliminate any size related growth differences, and second to determine which seedlings are inherently more efficient (South, 1995). There was no significant difference of MRGR between direct-seeded and nursery-grown plants at both sites possibly because the time for comparison (one rainy season after transplanting) was too short. Direct seeded plants, grown from late sowing, showed higher MRGR of RCD and crown than nursery-raised plants because the rainy season after transplanting might be 1st growing season for them to perform in the field while direct seeded plants germinated from early sowing had enough time to grow during 1st rainy season after sowing.

A reduction in the root-shoot ratio is almost always in response to more favorable growing conditions. An increase in the root-shoot ratio, on the other hand, would indicate that a plant was probably growing under less favorable conditions (Harris, 1992). However, tree species with high root:shoot ratio are indeed likely to accumulate more total non-structural carbohydrates (TNC) than tree species with low root:shoot ratio (Chapin et al., 1990), and sufficient TNC and nutrients are needed for seedlings to regenerate shoots and leaves when re-sprouting (Lahoreau et al., 2006). There was no significant difference in root/shoot ratio of nursery-raised plants compared with those grown from direct seeding, despite the difference in the favourability of conditions between the two sites.

Fertiliser application had no effect on growth performance, MRGR, dry weight and root/shoot ratio of seedlings after the second rainy season when considered each site separately. In contrast to Nussbaum et al. (1995) and Hua and Corlett (2003), adding nutrients was not enhanced early seedling growth on degraded areas. Tree species require different type and amount of essential nutrients for their growth in various habitats (Van Breugel et al., 2010) and it is possible that the small amounts of additional fertiliser did not exceeded loses due to leaching, denitrification and immobilization, and hence available nutrients did not meet plant requirements. Moreover, in the area where soils are extremely poor, seedlings of tropical trees showed lack of positive response to fertilization (Ganade & Brown, 2002).

6.4.2 Comparing costs and establishment

Direct seeding was less expensive and labour intensive than planting nursery-raised plants. Establishment of direct seeded plants could save about 30%. There was no significant difference of no. of seedlings at the end of 2nd rainy season after sowing but direct-seeded plants grew twice as fast on average. A total of 2797 and 2919 stems ha-1 of direct seeded and nursery-raised plants respectively survived in the field at 18 month after early sowing. The total stand density of direct seeded plants is considerably higher comparing to the study of Engel and Parrotta (2001) in Brazil which ranged from 1050 to 1790 stems ha-1 of two pioneer legume species (*Enterolobium contorstisiliquum* and *Schizolobium parahyba*) dominance, however the costs of this study were about 5 times higher with 5- fold difference of species diversity.

Major cost of direct seeding in this study was the plastic tubes to prevent the seeds from moving (about 24% of total cost). If this material was eliminated or replaced, the cost is still about 4 times higher with double number of species survived when compared with the study of Cole et al. (2011) that they sown five species of late-successional trees in pasture areas in Costa Rica.

As mentioned by Doust et al. (2008) establishing diverse rainforest species mixtures by direct sowing a range of species that vary in their seed morphology and ecological niches for establishment will be difficult to achieve from a single sowing event, however the results of this study indicate that it is possible to establish about 10 species from single sowing with above 2700 stems ha-1 survived at 18 months after sowing.

In conclusion, this study was able to fairly compare the costs and early achievement between direct seeding and planting method. The results suggest that direct seeding could save about 30% with equal quantity and diversity, and better growth performance of successfully established tree species, about 10 species at above density 2700 stem ha-1. Moreover, there was apparently different when comparing cost per tree, 33 and 45 baht for direct-seeded and nursery-grown plant respectively. Nevertheless, in further study if the plastic tubes are removed, direct seeding could save about 50% with half cost per tree comparing to planting the nursery-grown seedlings, or replacing the plastic tubes with biodegradable materials might be an option. Excellent growth performance of direct seeded plants was demonstrated with means of all measured growth parameters being twice as large as compared to nursery-raised plants at 18 months after sowing the seeds in the beginning of rainy season. Although there was no difference in inherent growth efficiency, direct seeded plants showed lower root/shoot ratio, which revealed that they had responded better to the growing conditions. This study also highlights the minimum management that soil nutrient supply was not required during the first two years after sowing. To this end, a single sowing could provide successful establishment of quite a number of tropical tree species in southern Thailand.

Chapter 7

Species relevance and the achievement of direct seeding

7.1 Introduction

Restoration establishes vegetation in denuded sites, or modifies existing vegetation in an already occupied site. Assembling a desired suite of species by planting or removal is an approach of restoration (Lockwood, 1997), and vegetation dynamic occurs as a result of the differential availability of species in or arriving and the differential performance of species at an arena (Pickett & Kolasa, 1989). Differential species performance results from the innate architectural and physiological features of the species life history strategies, and the interactions of plants with surrounding environments (Pickett et al., 2001). Ecologists have traditionally divided forest trees into "pioneer" and "climax" species. The distinctions between these two groups is not always that clear since they form the extremes of a continuous life history gradient (Slik et al., 2003; Swaine & Whitmore, 1988), however some studies have emphasized using morphological plant characteristics (wood density, seed size and leaf shape) associated with the pioneer–non-pioneer life history strategy (Alvarez-Buylla & Martinez-Ramos, 1992; Brzeziecki & Kienast, 1994; Swaine & Whitmore, 1988). A lack of ecological data is a major cause why the successional status of most tropical species is still unknown (Slik, 2005). Nevertheless, a few studies like Smith et al. (1997) and Ashton et al. (2001) have proposed finer levels of successional status, such as "regeneration guilds", based on mode of dispersal and life history traits which could be used as guidelines for basic classification.

Pioneer species have most commonly been used for direct seeding because they occur naturally at the early stages of succession (Balandier et al., 2009; Engel &

Parrotta, 2001; Garcia-Orth & Martínez-Ramos, 2008; Sun et al., 1995) and their seeds tend to germinate rapidly (Snell & Brooks, 1997; Sun et al., 1995). For example, *Alphitonia petriei* was used in northern Australia because of its fast growing habit, which generates rapid crown formation (Doust et al., 2006, 2008; Engel & Parrotta, 2001). The rapid growth of pioneer species can shade out weeds soon after the crown closure is gradually achieved (Doust et al., 2008). However, pioneer species tend to have small seeds with dormancy (Dalling & Hubbell, 2002) and they are less of stresses, as explained in the tolerance-fecundity trade-off theory (Muller-Landau, 2010).

A few previous studies suggest that lager-seeded tree species are more promising for direct seeding (Carmago et al., 2002; Doust et al., 2006; Hardwick et al., 1997; Hooper et al., 2002) but results among habitat types have generally varied considerably. For example, Doust et al. (2008) reported that large seeds of late-successional species establish well in degraded areas of Australia, and Carmago et al. (2002) reported that larger-seeded species could grow on degraded, bare ground and in pastures, but that seedlings survived less well in successional and mature forest in the Central Amazon. In contrast seedling survival of large-seeded, late-successional trees was higher under tree plantation compared to secondary forests or pasture in southern Costa Rica (Cole et al., 2011). Slow growing habit of larger seeded species might limit their contribution to early site capture (Doust et al., 2008). However, the key advantage of large seeds appears to be their tolerance of stresses since higher resources can be allocated to tolerate particular stresses such drought or shade (Coomes & Grubb, 2003; Muller-Landau, 2010).

Fruits and seeds of tropical tree species vary widely in their size and morphology and are dispersed by a broad array of dispersal agents (Levey et al., 1994; Muller-Landau & Hardesty, 2005). Understanding seed dispersal is critical to understanding plant population and community dynamics (Nathan & Muller-Landau, 2000; Wang & Smith, 2002). Among species with same dispersal syndromes, further variation in fruit and seed characteristics may affect seed dispersal patterns and subsequently recruitment success. Species with some characteristics in common could only establish well in some particular sites and these compatible matches would benefit to select suitable species for direct seeding. Many studies have shown that various herbaceous and trees, nitrogen-fixing legumes can protect soil surfaces, retain soil moisture, improve soil fertility, and retard ground fires (Ashton et al., 1997). For example, tree legume plants (*Enterolobium contortisiliquum* and *Schizolobium parahyba*) showed better establishment and growth performance than other groups of species tested during the first 2 years after sowing, on degraded lands in Brazil (Engel & Parrotta, 2001).

Other views of related traits of plants should be considered to increase potential criteria for selecting the suitable direct-seeded candidates. Thus the objective of this study was to find out if some species traits (sucessional status, types of fruit and dispersal mode) had contributed to higher successful colonisers on abandoned areas, and higher achievements of direct seeding (germination, establishment, growth performance and relative growth rate) on different sowing time.

7.2 Materials and methods

Germination data (see Chapter 4), establishment rate and growth data at the end of 2nd rainy season after sowing (see Chapter 6) were collated and tabulated for calculation across families, sucessional status, type of fruit and dispersal mode. If the same species was tested at both study sites, the best results were used in the analysis. A Generalized Linear Model (GLM) was used to identify the impact of taxonomic relation, sucessional status, type of fruit and dispersal mode on germination and establishment percentage due to non-constant variance in proportion. ANOVA was used to analyze growth data (RCD, height, crown width and biomass) if normal distribution and homogeneity were detected, otherwise GLM was used. Mean comparisons were carried out by treatment contrast (p=0.05). All statistical analyses were performed using the statistical software R 2.11.1 (R Development Core Team, 2010).

The suitability score or percentage (0-100) of maximum possible score with available data, based on species field performance (survival and growth) at the end of 2nd rainy season after sowing, was calculated to predict which tree species are suitable for restoration by direct seeding in southern Thailand. First, all species that have survival percentage less than 10 by the end of 2nd rainy season (expressed as a percentage of seed sown) was rejected. Then for all those species which exceed the threshold was applied the suitability index with the below formula:

Survival * Size

By survival is the number of seedling alive at end of 2nd rainy season expressed as a percent of seeds sown, and height was selected to represent the size in the formula. Importantly, size should have equal weight as survival in the calculation to get the raw suitability score. All raw score was divided by the highest raw value and multiply by 100 to get a rank score.

Table 7.1 List of study species

Species	Family	Successional status [a]	Dispersal mode	Fruit type	Sowing time [b]
Alstonia macrophylla Wall. ex G. Don	Apocynaceae	Pioneer	Anemochorous	Follicle	L1
Archidendron clyperia (Jack) Niels.	Leguminosae	Pioneer	Zoochorous	Pod	E1
Artocarpus dadah Miq.	Moraceae	Climax	Zoochorous	Compound	E1
Callerya atropurpurea (Wall.) Schot	Leguminosae	Climax	Zoochorous	Pod	E2
Calophyllum soulattri Burm. f.	Guttiferae	Climax	Zoochorous	Drupe	L1
Canthium glabrum Bl.	Rubiaceae	Pioneer	Zoochorous	Drupe	L2
Cinnamomum iners Reinw. ex Bl.	Lauraceae	Climax	Zoochorous	Berry	E1
Diospyros oblonga Wall. ex G. Don	Ebenaceae	Climax	Zoochorous	Berry	E2,L2
Diospyros pilosanthera Blanco	Ebenaceae	Climax	Zoochorous	Berry	E2,L2
Elaeocarpus stipularis Bl.	Elaeocarpaceae	Climax	Zoochorous	Drupe	L2
Garcinia cowa Roxb.	Guttiferae	Climax	Zoochorous	Berry	E2
Garcinia hombroniana Pierre	Guttiferae	Climax	Zoochorous	Berry	E1
Garcinia merguensis Wight	Guttiferae	Climax	Zoochorous	Berry	E1
Lepisanthes rubiginosa (Roxb.) Leenh.	Sapindaceae	Climax	Zoochorous	Drupe	E1
Litsea grandis (Wall. ex Nees) Hk.f.	Lauraceae	Climax	Zoochorous	Berry	E1

Table 7.1 (Continued)

Species	Family	Successional status [a]	Dispersal mode	Fruit type	Sowing time [b]
Microcos paniculata L.	Tiliaceae	Pioneer	Zoochorous	Drupe	E2,L1
Morinda elliptica (Hk.f.) Ridl.	Rubiaceae	Pioneer	Zoochorous	Compound	E2,L2
Pajanelia longifolia (Willd.) K. Sch.	Bignoniaceae	Pioneer	Anemochorous	Pod	E1
Palaquium obovatum (Griff.) Engl.	Sapotaceae	Climax	Zoochorous	Berry	E1
Peltophorum pterocarpum (DC.) Back. ex K. Hey.	Leguminosae	Pioneer	Anemochorous	Pod	L1,E2,L2
Sandoricum koetjape (Burm.f.) Merr.	Meliaceae	Climax	Zoochorous	Drupe	E2
Scolopia spinosa (Roxb.) Warb.	Flacourtiaceae	Climax	Zoochorous	Berry	E1
Sindora siamensis Teysm. ex Miq.	Leguminosae	Climax	Anemochorous	Pod	L1
Terminalia citrina (Gaerth.) Rox. Ex	Combretaceae	Climax	Zoochorous	Adrupe	L1,L2
Vitex pinnata L.	Verbenacea	Climax	Zoochorous	Drupe	L1,E2,L2

[a] Successional status (following criteria of Ashton et al., 2001)

[b] Sowing time: E1= Early sowing (May 2009); L1 = Late sowing (October 2009) in Krabi; E2 = Early sowing (September 2009); L2 = Late sowing (December 2009) in Nakhon Si Thammarat

7.3 Results

A total of 13 and 8 families were tested for early and late sowing respectively. All could germinate. However, with early sowing, no seedlings of species in the family Bignoniaceae species survived until the end of the 2^{nd} rainy season and likewise, no seedlings in the families; Combretaceae, Guttiferae and Rubiaceae with late sowing.

7.3.1 Germination and establishment

Tree species that could germinate successfully in the field showed higher survival probability. Species in the Ebenaceae had significantly the highest germination percentage in early sowing, followed by Meliaceae, Moraceae, Rubiaceae and Tiliaceae ($p<0.05$) (Figure 7.1a). Furthermore 3 of these families (Ebenaceae, Moraceae and Tiliaceae) also showed significantly high relative establishment percentage (about 20-30%) at the end of 2nd rainy season after sowing ($p<0.05$) (Figure 7.1b). In addition, Leguminosae and Verbenaceae species were grouped with these 3 families regarding high establishment percentage ($p<0.05$) (Figure 7.1b).

With late sowing the germination percentage was low for all families (<40%) and only legume species showed significantly higher establishment rate about 20% ($p<0.05$) (Figure 7.2a and 7.2b).

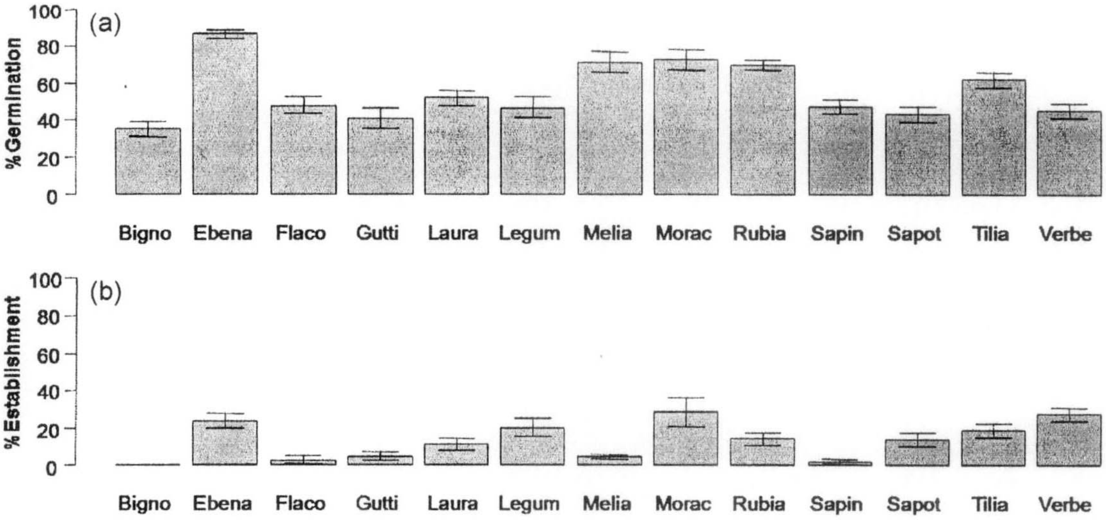

Figure 7.1 Mean percentage (a) germination and (b) establishment of early-sown species across families

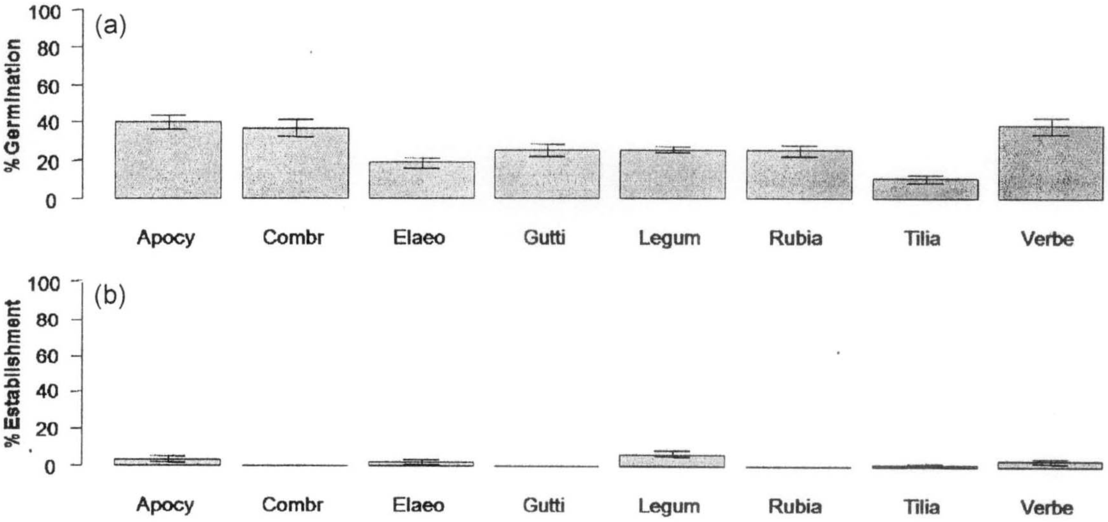

Figure 7.2 Mean percentage (a) germination and (b) establishment of late-sown species across families

Climax and pioneer species did not differ significantly in terms of mean percentage germination and establishment for both sowing times (Table 7.2 and 7.3).

Zoochorous species exhibited significantly higher germination than anemochorous species in early sowing but this did not contributed to significantly higher establishment percentage at the end of 2nd rainy season as it seemed to be (Table 7.2). In contrast, there was no significant differences in germination percentage between anemochorous and zoochorous species when sown late in the late rainy season but anemochorous had higher survival rates at the end of 2nd rainy season (Table 7.3) than zoochorous species.

Species with seeds in pods exhibited significantly higher establishment success at both sowing times, whilst results varied for other fruit types ($p<0.05$) (Table 7.2 and 7.3).

Table 7.2 Mean percentage germination and establishment of early-sown species across successional stage, dispersal mode and fruit type (S.E.)

		% Germination	% Establishment
Successional stage			
	Climax	57.38a (2.15)	14.23a (1.60)
	Pioneer	49.00a (3.82)	10.78a (1.80)
Dispersal mode			
	Anemochorous	25.47a (3.54)	5.31a (1.37)
	Zoochorous	58.59b (1.87)	13.96a (1.38)
Fruit type			
	Berry	54.55b (2.97)	10.97a (1.63)
	Compound	71.17c (3.26)	21.50b (4.72)
	Drupe	59.31b (3.06)	11.00a (1.95)
	Pod	44.77a (4.43)	20.00b (4.65)

Table 7.3 Mean percentage germination and establishment of late-sown species across successional stage, dispersal mode and fruit type (S.E.)

		% Germination	% Establishment
Successional stage			
	Climax	28.62a (1.97)	3.23a (0.83)
	Pioneer	25.31a (2.13)	4.06a (1.10)
Dispersal mode			
	Anemochorous	30.31a (2.22)	5.42b (1.14)
	Zoochorous	25.54a (1.82)	1.88a (0.59)
Fruit type			
	Adrupe	36.88b (4.38)	-
	Compound	17.81a (4.54)	-
	Drupe	24.81a (2.04)	1.88a (0.59)
	Follicle	40.00b (3.66)	3.12b (1.62)
	Pod	25.47a (1.87)	6.56b (1.46)

7.3.2 Growth performance and relative growth rate

Two out of 12 families (Leguminosae and Moraceae) showed excellent growth performance at the end of 2nd rainy season after sowing. Their mean RCD, height and crown width exceeded 20 mm, 100 and 60 cm respectively (Figure 7.3). The second best groups were Flacourtiaceae, Lauraceae and Sapotaceae which exhibited significantly larger mean RCD and crown width than others (Figure 7.3). Ebenaceae and Sapindaceae seedlings also exhibited significantly lower values for all growth parameters (Figure 7.3).

A similar pattern was observed for all measured growth results in studied species grouped by family. A higher RCD was associated with taller and seedlings with broader crowns. Apocynaceae and Leguminosae showed significantly better growth performance in late-sown batch (Figure 7.4).

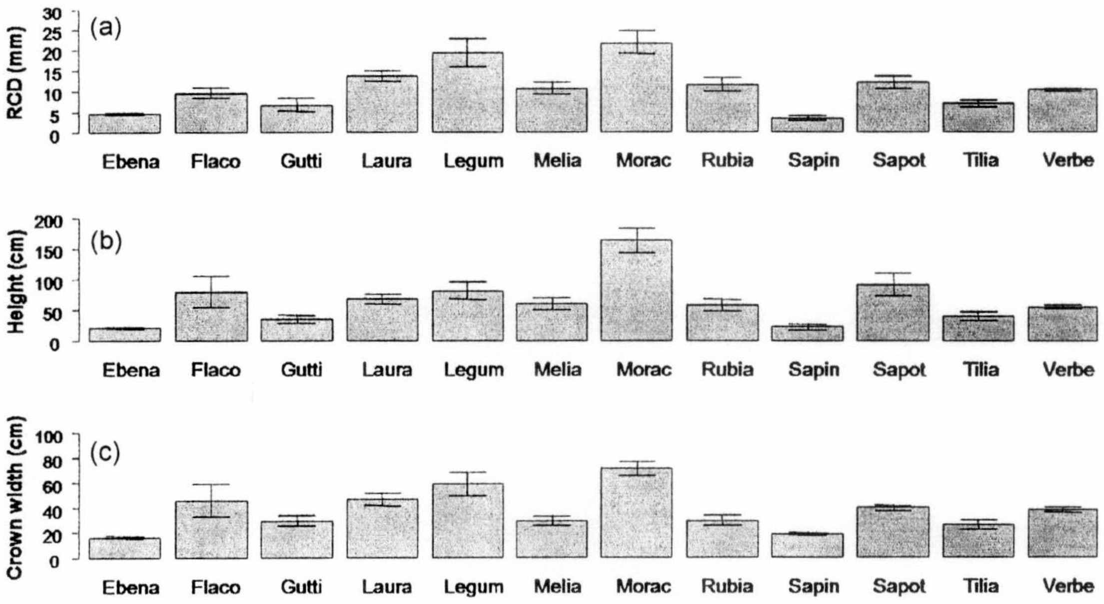

Figure 7.3 Growth performances of early-sown species; mean (a) RCD, (b) height and (c) crown width at the end of 2nd rainy season after sowing

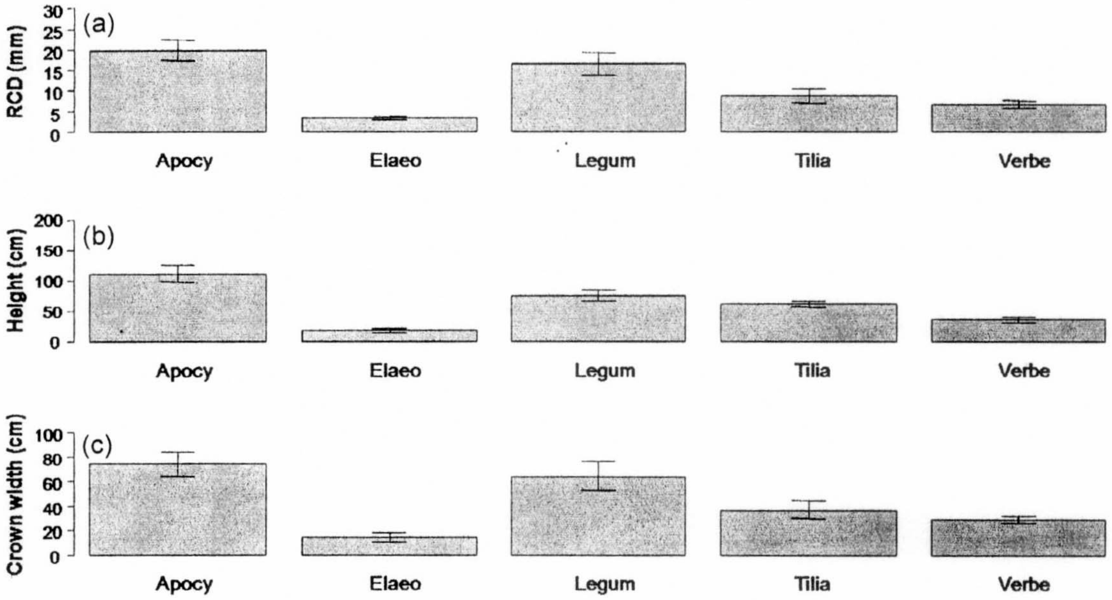

Figure 7.4 Growth performances of late-sown species; mean (a) RCD, (b) height and (c) crown width at the end of 2nd rainy season after sowing

In general, there were no significant differences in growth performance among successional stages and dispersal mode for early sowing. Only the mean RCD of pioneer species was significantly higher than that of climax species. Similarly, anemochorous species developed significantly higher mean RCD than zoochorous species at the end of 2nd growth season ($p<0.05$) (Table 7.4). In contrast, for late sowing, the means of all measured growth parameters were significantly higher for pioneer and anemochorous species than for climax and zoochorous species respectively in late sowing ($p<0.05$) (Table 7.5).

Species with fleshy fruits produced significantly smaller seedlings at both sowing times. The seedlings produced from berries and drupes were significantly smaller than those from other fruit types, whilst the seeds from pods produced seedlings with excellent growth and developed significantly larger mean RCD, height and crown width (Table 7.4 and 7.5). In addition, seeds from compound fruits developed into significantly bigger seedlings from early sowing (Table 7.4).

Table 7.4 Growth performances of early-sown species across sucessional stages, dispersal modes and fruit types (S.E.)

	RCD (mm)	Height (cm)	Crown width (cm)
Successional stage			
Climax	10.41a (0.69)	61.35a (5.40)	35.58a (2.07)
Pioneer	16.50b (2.75)	73.49a (11.19)	47.63a (7.78)
Dispersal mode			
Anemochorous	19.81b (3.61)	63.21a (15.58)	53.68a (10.72)
Zoochorous	11.35a (0.89)	64.41a (5.16)	37.46a (2.54)
Fruit type			
Berry	8.70a (0.75)	49.21a (5.45)	31.07a (2.42)
Compound	17.62b (2.18)	118.04c (18.90)	51.92b (7.23)
Drupe	9.03a (0.72)	49.91a (4.38)	29.62a (2.06)
Pod	18.97b (3.31)	80.17b (13.71)	58.06b (8.98)

Table 7.5 Growth performances of late-sown species across sucessional stages, dispersal modes and fruit types (S.E.)

	RCD (mm)	Height (cm)	Crown width (cm)
Successional stage			
Climax	6.02a (0.62)	35.32a (4.17)	23.91a (2.34)
Pioneer	19.08b (2.03)	93.54b (8.03)	75.53b (8.19)
Dispersal mode			
Anemochorous	17.34b (2.10)	84.93b (8.88)	66.72b (8.98)
Zoochorous	6.02a (0.80)	36.40a (5.37)	26.31a (3.46)
Fruit type			
Drupe	6.02a (0.80)	36.40a (5.37)	26.31a (3.46)
Follicle	19.75b (2.44)	112.50b (13.92)	73.88b (9.95)
Pod	16.46b (2.73)	74.90b (9.58)	64.12b (11.86)

During 2nd rainy season after sowing, there were no significant differences in MRGR of RCD between families, dispersal modes and fruit types for both sowing times (Table 7.6 and 7.7). Most families that exhibited significantly higher MRGR of height also had higher MRGR of crown width for early sowing ($p<0.05$) (Table 7.6), whereas only Apocynaceae showed significantly higher MRGR of height than others in late sowing ($p<0.05$) (Table 7.7).

MRGRs of all measured growth parameters were not significant between pioneer and climax species in early sowing, but they did differ significantly for late sowing, with pioneer species showing significantly higher MRGR of RCD, height and crown width than climax species ($p<0.05$) (Table 7.7).

In overview, dispersal modes did not contributed to differences in mean MRGR of tested species at both sowing times. Only for late sowing did anemochorous species show significantly higher RGR of height ($p<0.05$) (Table 7.7).

No particular fruit type showed relatively high MRGR of all measured growth parameters. Berries showed significantly higher MRGR of height and crown in early sowing whilst follicles showed a similar pattern in late sowing ($p<0.05$) (Table 7.6 and 7.7).

Table 7.6 Mean relative growth rate (MRGR) of early-sown species (S.E.)

	MRGR of RCD	MRGR of height	MRGR of crown width
Family			
Ebenaceae	1.23a (0.16)	0.59a (0.06)	0.87ab (0.12)
Flacourtiaceae	1.32a (0.33)	1.95b (0.44)	1.36b (0.42)
Guttiferae	1.12a (0.31)	1.29b (0.09)	0.82a (0.12)
Lauraceae	1.27a (0.21)	1.59b (0.23)	1.84b (0.23)
Leguminosae	1.48a (0.20)	1.00a (0.18)	1.00b (0.14)
Meliaceae	0.68a (0.17)	0.58a (0.19)	0.52a (0.15)
Moraceae	1.50a (0.16)	1.34b (0.07)	1.40b (0.08)
Rubiaceae	1.09a (0.26)	0.75a (0.12)	0.31a (0.07)
Sapindaceae	1.08a	0.98a	1.24b
Sapotaceae	1.17a (0.19)	1.65b (0.20)	1.05b (0.11)
Tiliaceae	1.23a (0.20)	0.69a (0.06)	0.81a (0.13)
Verbenaceae	1.00a (0.12)	0.76a (0.08)	0.71a (0.05)
Successional stage			
Climax	1.16a (0.07)	1.03a (0.07)	1.05a (0.07)
Pioneer	1.39a (0.17)	0.98a (0.14)	0.80a (0.13)
Dispersal mode			
Anemochorous	1.94a (0.50)	0.74a (0.16)	0.67a (0.19)
Zoochorous	1.17a (0.06)	1.04a (0.07)	1.01a (0.06)
Fruit type			
Berry	1.22a (0.10)	1.21b (0.11)	1.18b (0.10)
Compound	1.09a (0.26)	0.75a (0.12)	0.31a (0.07)
Drupe	0.97a (0.10)	0.68a (0.07)	0.70a (0.07)
Pod	1.49a (0.14)	1.10ab (0.13)	1.13b (0.10)

Table 7.7 Mean relative growth rate (MRGR) of late-sown species (S.E.)

	MRGR of RCD	MRGR of height	MRGR of crown
Family			
Apocynaceae	3.74a (0.23)	3.72b (0.14)	3.10a (0.63)
Elaeocarpaceae	1.76a (0.44)	1.29a (0.27)	1.48a (0.27)
Leguminosae	2.46a (0.29)	2.24ab (0.30)	1.61a (0.23)
Tilliaceae	2.29a (0.38)	2.81ab (0.76)	2.68a (0.48)
Verbenaceae	2.43a (0.60)	1.50a (0.36)	1.69a (0.44)
Successional stage			
Climax	2.00a (0.30)	1.36a (0.18)	1.40a (0.23)
Pioneer	3.18b (0.19)	3.22b (0.19)	2.60b (0.23)
Dispersal mode			
Anemochorous	2.80a (0.26)	2.63b (0.28)	2.01a (0.29)
Zoochorous	2.22a (0.34)	1.71a (0.28)	1.83a (0.27)
Fruit type			
Drupe	2.22a (0.34)	1.71a (0.28)	1.83ab (0.27)
Follicle	3.74a (0.23)	3.72b (0.14)	3.10b (0.63)
Pod	2.46a (0.29)	2.24a (0.30)	1.61a (0.23)

7.3.3 Suitability scores

All species had expressed percent survival higher than the threshold was the early-sown batch. The scores were likely fluctuated and this is possibly because the growth performance of *A. dadah* was very outstanding, and this had caused a big difference between its score and other species. From the rank score; 2 species had achieved suitability scores higher than 40, they were *A. dadah* and *C. atropurpurea*; 8 species achieved acceptable scores (10-40%) (*C. iners*, *D. oblonga*, *G. hombroniana*, *L. grandis*, *M. paniculata*, *M. elliptica*, *P. obovatum* and *V. pinnata*); and one species achieved the lowest score, *D. pilosanthera*, this species expressed the smallest seedlings by the end of 2nd rainy season (Table 7.8).

None of late-sown species expressed percent survival higher than 10, all of them were rejected from the calculation including eight species from early sowing; *A. clyperia*, *G. merguensis*, *G. cowa*, *L. rubiginosa*, *P. longifolia*, *P. pterocarpum*, *S. koetjape* and *S. spinosa*.

Table 7.8 Suitability score of studied species in both sowing times

Species	Family	Establishment (%)	Height (cm)	Raw suitability score	Rank Suitability score (0-100%)
A. dadah	Moraceae	28.44	163.45	4,648.22	100.00
C. atropurpurea	Leguminosae	49.69	44.59	2,215.38	47.66
V. pinnata	Verbenaceae	26.88	54.35	1,460.56	31.42
P. obovatum	Sapotaceae	13.44	91.49	1,229.45	26.45
D. oblonga	Ebenaceae	37.50	25.48	955.69	20.56
L. grandis	Lauraceae	11.56	73.08	844.96	18.18
M. elliptica	Rubiaceae	13.75	57.82	795.08	17.11
M: paniculata	Tiliaceae	18.44	39.87	735.10	15.81
C. iners	Lauraceae	10.00	62.84	628.37	13.52
G. hombroniana	Guttiferae	13.13	41.06	538.87	11.59
D. pilosanthera	Ebenaceae	10.00	17.00	169.96	3.66

7.4 Discussion

Some traits such as seed or seedling types are strongly influenced by "phylogenetic inertia" at the genus, family and even higher order clades (Ibarra-Manríquez et al., 2001). However, species performance also depends on ecological strategies, revealed by suites of traits, conferring different relative ecological advantages in different environments (Wishnie et al., 2007). A total of 16 families with relatively few species members were used in the study according to seed availability; each family had 2 species (Ebenaceae, Lauraceae and Rubiaceae), 3 species (Leguminosae), 4 species (Guttiferae) and only one species for the others.

Although it seems to be too rough for drawing general idea from relatively small number of speciose families, however this finding should benefit for at least to give an idea on which traits conferring to early achievement of direct seeding on degraded areas. None of Bignoniaceae species with phanerocotylar seedling could survive at the end of 2nd rainy season from early-sown batch while Ebenaceae, Leguminosae, Moraceae, Tiliaceae and Verbenaceae showed relatively high establishment rate whose most seedlings are cryptocotylar.

Seedlings of different types have different light requirements (De Vogel, 1980; Fenner & Thompson, 2005) and this adaptive value has been explored analyzing seedling performance under environmental conditions that characterize open and closed-crown forest patches (Ibarra-Manríquez et al., 2001). Bignoniaceae was a very diverse family; phanerocotylar epigeal with foliaceous cotyledons (PEF) was the most dominant seedling type in lowland rain forest in Mexico (Ibarra-Manríquez et al., 2001), this type were significantly overrepresented among pioneer species (Ibarra-Manríquez et al., 2001) and generally grew faster than seedling with other types when they were exposed to increased light (Popma & Bongers, 1988). Nevertheless, the fast-growing ability had not contributed to successfully establish on degraded areas in southern Thailand if young seedling with soft structure could not survive in harsh condition. In contrast the mid-crown species in Moraceae with cryptocotylar hypogeal with reserve storage or absorption cotyledons had heavy large seeds (Ibarra-Manríquez et al., 2001) and able to develop in stress condition (Muller-Landau, 2010). This experiment had not put an effort on describing types of seedling, therefore to explain the relationship between seedling type and the success of direct seeding is impossible and the study on the seedling traits regarding taxonomic relations is further needed. In fact, not only types of seedling but understanding of morphological structures and phylogenetic patterns under vary conditions would be benefit for direct seeding technique.

In addition, Legume species had been mentioned for their ability to fixing nitrogen (Cervantes et al., 1996; Garg, 1999; Siddique et al., 2008). They had various types of seedling in the study of Ibarra-Manríquez et al. (2001) and showed excellent growth in both sowing times in this study which emphasizing the suitability to be used in rehabilitation on degraded and eroded soil (Cervantes et al., 1996; Garg, 1999).

Early successional species produce many small well-dispersed seeds, whereas late successional species invest in few large offspring with higher probability of survival and establishment (Fenner & Thompson, 2005). However, seed preparation before sowing had selected only good quality of seeds, this had increased higher probability to get viable seeds equally between early and late successional species. Thus germination and establishment were not different among these traits.

The successional status of most species is still unknown in the tropics (Slik, et al., 2003) since lacking of ecological data, however tree growth rate might be helpful to differentiate between slow and fast growers, which could be used to discriminate between early and late sucessional species (Slik, 2005; Swaine & Whitmore, 1988). The results from late sowing showed that all measured growth parameters (RCD, height and crown) and relative growth rate of early successional species were higher than late successional species.

In contrast, none of growth parameters and relative growth rate was different between early and late successional for group of studied species sown in the beginning of rainy season, except mean of RCD. Among early-sown climax species, there were *A. dadah* and *C. atropurpurea* that their growth was markedly excellent over the pioneer species. In this case, the growth rate in early recruitment stage alone might not be used to discriminate pioneer and climax species since they form the extremes of a continuous life history gradient (Slik, 2005; Slik et al., 2003). Some climax species could reach equal size with pioneer species in early establishment (Cole et al., 2011; Engel & Parrotta, 2001; Sun et al., 1995). Moreover, crown was possibly harmed during weeding and thus height and crown width might not be suitable for actual comparison. The study of Buell-Small succession revealed that late successional species are present from the start of the succession, they might probe the environment repeatedly before becoming established (Rankin & Pickett, 1989). Indeed, seeding or planting late successional species is the practice parallel to this natural pattern (Pickett et al., 2001).

Fruit type reflects an adaptation to dispersal (Schmidt, 2007). Most tree seeds are either dispersed by wind or by relatively large animals (birds or mammals). Animal-dispersed seeds are often quite large and conspicuous, and often contain protective structures around the seeds (Schmidt, 2007). These characters had enabled early-sown zoochorous seeds to survive and germinate better than anemochorous seeds when sufficient moisture was achieved. Although mean of establishment percentage of zoochorous was higher than anemochorous species, but statistically it was not significant, this might be caused by very varied results from zoochorous species (0-65%) and thus created huge variance. Mode of dispersal was not contributed to higher recruitment success at the end of 2nd rainy season in this study due to many factors involved such as competition, desiccation and herbivory. These obstacles were possibly acted as the interactive barriers, and thus only some species could survive and consequently establish after germination.

Nevertheless, zoochorous species had not showed better germination percentage than anemochorous species in late rainy season. Lacking of sufficient moisture after sowing might create unsuitable condition for germination (Fenner & Thompson, 2005) or dry out animal-dispersed seeds which most fleshy. Although wind-dispersed species are typically pioneer colonizers and fast-growing (Dalling et al., 1997; Vazquez-Yanes & Orozco-Segovia, 1993), however they were not expressed significantly better MRGR during the first 2 rainy season after sowing. This is possibly because the growth of tree seedlings, especially in their early stage, can be strongly affected by soil properties (Nussbaum et al., 1995; Woodward, 1996), particularly the case for pioneer species as a consequence of their small seeds and rapid growth habits (Chapin et al., 1986).

Legume species typically produce seeds in pods (Dallwitz et al., 2011), they showed higher establishment in both sowing times possibly because their nitrogen fixing capabilities (Engel & Parrotta, 2001) enabled them to survive on degraded areas with excellent growth performance. In contrast fleshy fruits (such as berry and drupe) are majority of animal-dispersed plants (Schmidt, 2007) and mostly produced from late-successional species (Pedro Jordano, 2000). They produced significantly smaller seedlings, which grew slowly and possibly being dormant until suitable condition has created (Fenner & Thompson, 2005; Whitmore, 1989).

Although the species with high germination (>85%) has been suggested to be candidate for direct seeding into the field by the study of Smith et al. (2008), however many factors such as absence or presence of dormancy (Travlos et al., 2007), differences in growth rates, hardiness, competition, and availability of seeds (Vazquez-Yanes & Orozco-Segovia, 1993) that also condition the success of direct seeding. Moreover, Guariguata and Ostertag (2001) stated that vegetation recovery of is heavily dependent on interactions between site-specific factors and land use, which makes it extremely difficult to predict successional trajectories in anthropogenic settings. From this study, the species with high germination had not guaranteed to exist in subsequent years, therefore the suitability score was calculated from establishment percentage and growth performance at the end of 2nd rainy after sowing. Species with suitability scores exceeding 40 should be suggested to be the excellent candidates for direct seeding; *A. dadah* and *C. atropurpurea*. Moreover, 8 species with acceptable scores (10-40%) should be additionally included into the list (*C. iners*, *D. oblonga*, *G. hombroniana*, *L. grandis*, *M. paniculata*, *M. elliptica*, *P. obovatum* and *V. pinnata*). Although two legume species (*A. clyperia* and *P. pterocarpum*) expressed percent survival lower than 10 and they were excluded at the first step, but due to their excellent growth performance, it is worth to test seed pre-treatment technique in further study to increase the germination rate and possibly contribute to higher survival. All of species has been suggested here is the early-sown batch which emphasizing the suitability of sowing the seeds in the beginning of rainy season is the critical point for species choice and appropriate timing.

All recommended candidate species for direct seeding in this study are common species with broad distribution throughout the region, most of them can be found in Indochina and some distribute over the Southeast Asia. Species may be common for different reasons. They may be eruptive or cyclical and hence periodically common (Krebs et al., 2001; Robin et al., 2009), or specialized on widespread environmental conditions, or generalists capable of exploiting a wide range of environmental conditions. To recommend those 12 common species to be the potential candidates for direct seeding, not because only they showed better success of establishment and growth performance, but conservation of common species is important for many reasons. These include, common species play particularly important roles in ecosystems including propagule dispersal, pollination, as well as comprising pivotal parts of food webs (Gaston, 2010; Sekercioglu, 2006), also common species may be those that are most likely to best adapt to rapid climate change (Steffen et al., 2009), may be those most useful as indicators of environmental change (McGeoch, 1998), and those most practical for some kinds of ecological monitoring (Devictor et al., 2010).

A weak point of this study was the small number of replicates within each taxonomic and functional group due to the limitation of seed availability. This explanation had drawn from a few years experiments which were conducted in two locations and tried to make simple understanding from complex system. Varying results from different sowing time could not be determined whether they happened because of different tested species or different time. However, some species expressed their suitability to be sown for a certain period of the year.

In summary, species of Ebenaceae, Leguminosae, Moraceae, Tiliaceae and Verbenaceae were successful colonizers on abandoned areas, which showed mostly excellent growth performance particularly the two families, Leguminosae and Moraceae. Species with fleshly fruits and mostly dispersed by animal seem to be high potential candidates for seed sowing in early rainy season. In addition, Apocynaceae had satisfactory results in terms of growth performance in late sowing along with legume species. Therefore early successional wind-dispersed species with dry fruits are recommended for sowing the seeds in late rainy season if it is only an option available.

Chapter 8

Overall discussion

8.1 Factors affecting direct seeding success

Having an accessible and reliable seed source is the first consideration when proposing direct seeding. Phenology studies are therefore important for determining where and when the seeds are ready for collection. This helps with scheduling appropriate times for seed harvesting and provides information on what species are available throughout the year. Fruit ripening is concentrated near the end of dry season with an additional peak in the early dry season on the east coast and in the middle of the rainy season on the west coast of southern Thailand (Chapter 3). An effective screening system is critical for species selection from among the very large number of tree species that typify tropical forest ecosystems. Seed size, shape and moisture content can all be used as guidelines with about 80% capability to explain the early success of direct seeding. Intermediate to large seed size and oval to round seed shape have been suggested to be high potential candidates while the seeds with low to medium moisture content have been classified to have moderate ability (Chapter 4). To increase the probability of selecting suitable species for direct-seeding other related plant traits should also be considered. Fruit type and dispersal mode have different effects at different sowing times. Animal-dispersed species and fleshy fruits appear to contribute to higher germination and establishment with early sowing (about twice as much) whereas wind-dispersed species with dry fruits achieved higher germination in late sowing. Legume species with seeds in pods have expressed satisfied results in both sowing times (Chapter 7). If species with all potential traits does not available during the appropriate time for sowing, seed storage will be required with the minimum cost to keep direct seeding as the low cost technique.

Simple storage conditions (10° C refrigerator) appeared to be adequate to maintain viability of *Peltophorum pterocarpum* seeds for 3 months (Chapter 5). All these together explain potential screening criteria to pursuit the success of direct seeding with available seed sources.

Early sowing at the beginning of the rainy season guarantees sufficient moisture for germination (Khurana & Singh, 2001), and greater moisture protects seeds and seedlings from desiccation (Morris, 2000) and maximizes the time for established seedlings to grow (Vieira & Scariot, 2006). Species sown early had twice the germinate percentage and 7 times higher establishment percentage than those sown late in the rainy season. However growth performance varied with site conditions. Mulching and seed protection did not seem to create special "safe sites" for the seeds, since monthly rainfall was more than sufficient and few predators lived in the study sites. Moreover, adding fertilizer decreased establishment percentage and had no effect on early growth of direct seeded plants (Chapter 5 and 6). Therefore, the appropriate sowing and management regimes confer to affirm cost-effective tool with considerable achievement.

In addition, protecting sites from further disturbance such as herbivory and etc. will allow established seedlings to speed up successional processes to restore ecosystem biodiversity and structure.

8.2 Implications for efficient direct seeding technique in southern Thailand

While the southern forests are disappearing similar to other parts of Thailand, very sparse restoration activities in terrestrial ecosystems have been published in this region (FORRU, 2008b; Kai, 2008; Worapornpan, 2007), particularly the lowland forests which are home for high biodiversity (Chapter 1). Deforestation is a major cause of loss of biodiversity in southern Thailand, most clearing happens principally through agricultural expansion (rubber trees and oil palms), and thus a cost-effective restoration technique is required which is applicable on a large scale. It is possible that the factors affecting direct seeding success, identified by this study, will contribute to the achievement of viable restoration systems for lowland forest ecosystems in southern Thailand.

Here, I proposed the list of high potential candidates and appropriate management measures for efficient direct seeding technique in southern Thailand, which may also be used in the regions with likely similar flora and environments.

8.2.1 Species

Suitability scores were calculated to predict which tree species are suitable for direct seeding in southern Thailand (Chapter 7). Two species are recommended for sowing in the beginning of rainy season as the excellent species with higher score (>40); *A. dadah* and *C. atropurpurea*; 8 species will be additionally suggested they have acceptable suitability score (10-40%); *C. iners*, *D. oblonga*, *G. hombroniana*, *L. grandis*, *M. paniculata*, *M. elliptica*, *P. obovatum* and *V. pinnata*. In addition, two legume species (*A. clyperia* and *P. pterocarpum*) are served as an option since they expressed excellent growth performance but their germination rate were low and therefore they need seed pre-treatment to increase germination rate for allowing them to be the potential candidates.

In the case that the 12 species mentioned earlier are not available, other species should be selected with large or intermediate seed size, oval to round seed shape, and seeds with low to medium moisture content as potential high performance candidate species (Chapter 4). In addition, animal-dispersed species with fleshy fruits are recommended for direct seeding in early rainy season, whilst wind-dispersed species may be suitable for sowing in late season. Apart from those characteristics, legume species are particularly recommended (Chapter 7).

8.2.2 Management regime

Disturbances should be minimized in the target sites for restoration i.e. fencing and firebreak will be needed if cattle and fire are intense. Anthropogenic disturbance can be overcome by making clear the objectives of restoration activities and including them in an agreement with all stakeholders. Site preparation is the next step to counteract soil compaction and weed competition, which are main barriers to establishing seedlings by direct sowing (Cole et al., 2011; Doust et al., 2006, 2008; Sun et al., 1995). Soil should be loosened only around the spot for seed sowing, rather than completely loosening the soil over the entire area, to conserve below-ground carbon accumulation and also to protect vegetation propagules in the soil (Zheng et al., 2008). However, belowground competition is considered far more important than aboveground competition in the reforestation of grassland (Davis et al., 1998; Nepstad et al., 1990, 1991) and needs to be removed. Mechanical weeding can hamper natural regeneration as young natural seedlings are removed together with the weeds (Zhuang, 1997) whereas herbicide usage in reforestation in the tropics is still problematic (Hau, 1997). It is recommended that low-toxicity herbicide use is effective on clearing the weeds before planting in northern Thailand (FORRU, 2006b) and it would be possible to use on clearing the weeds before sowing in the south.

Some genetic considerations such as quality of mother trees, genetic variation, and site-source matching should be considered with seed collection (Schmidt, 2007), in addition, concerns of small populations have important applications for restoration practices, and should be kept in mind at all stages of native plant community restoration efforts (Knapp & Dyer, 1997). In the tropics where field trials contain analysis and documentation of genetic quality in not always available, good quality often becomes a pragmatic best available. However, there is growing recognition that seed collections should be made near the restoration site to ensure the genetic similarity of introduced and local populations, minimizing the probability of outbreeding depression (Hufford & Mazer, 2003). Moreover, collections must be made from a large enough number o individuals to represent population variation adequately and to avoid severe genetic bottlenecks. Ultimately, if seed zones are embarked in this region, to develop dynamic or 'floating' seed transfer zones (Ying & Yanchuk, 2006) that incorporate with both geography and shifting climates, it will help to maximize the viability of genotypes introduced in restoration, and thus to maintain evolutionary potential of threatened populations in the face of future environmental change (Hufford & Mazer, 2003). Failure to do so may lead to either immediate failure or longer-term collapse if the population does not possess phenotypes that allow it to survive and adapt to current and changing conditions over time (Kramer & Havens, 2009).

Phenological studies can be used to determine optimal seed collection times throughout the year for individual tree species (Chapter 3); however maturity indices such as colour change, hardening of fruit/seed coat, loosening of fruit pulp etc.

should be further examined. Seeds should be properly handled to achieve clean, pure seeds of high physiological quality which can be stored before suitable for sowing. Simple storage in air-tight container at room temperature or refrigerator at 10° C will help to promote direct seeding as the low cost technique.

Prepared seeds should be buried to have high establishment rate (Doust et al., 2006) in a certain depth depending on seed size, at the beginning of rainy season in southern Thailand. There should be a material holding the seeds still, to prevent seed lose from leaching or moving to unsafe site for germination. In addition, mulching by cut vegetations and seed exclusion are not necessary to protect the buried seeds on degraded areas in southern Thailand since there is sufficient monthly rainfall during rainy season and insect predators cannot be the problem if the intermediate and large seeds are used.

Weeding and adding fertilisers during rainy season after planting are recommended to increase the possibility of planted seedlings to survive and compete with surrounding vegetations (FORRU, 2006b). Three times application at 4-6 weeks interval during subsequent rainy season after planting is the standard maintenance of framework species method that implemented successfully in northern Thailand (FORRU, 2006b). Chemical weed control has the additional advantage of reducing soil erosion over mechanical weeding and cost effective (Tjitrosemito, 1986) but none of the study had been conducted in southern Thailand. Longer rainy season in southern Thailand will increase interval period between each event (about 6-8 weeks) and it might be applied less frequency because of heavy and continuing rain. Adding fertiliser is not required at early stage after sowing, it decreases establishment percentage during 1st year after sowing and shows no effect on growth of direct seeded plants during the first 2 years (Chapter 5 and 6).

8.2.3 Cost evaluation

A major advantage of direct seeding over planting is its low cost (Cole et al., 2011; Doust et al., 2006; Engel & Parrotta, 2001; Lamb & Gilmour, 2003) since costs of most activities in the nursery, for transport and for casual labour was reduced. For direct comparison, establishment of direct seeded plants could save about 30% (with less cost per tree) with comparable results regarding density of successfully recruit seedlings (about 2700 seedling ha $^{-1}$ and double size of seedlings) at the end of 2nd rainy season after sowing. The most expensive of direct seeding in this study is the PVC plastic tube to prevent the seeds from losing. Therefore the cost will be much more reduced if it has been replaced with other cheaper materials. Furthermore, direct seedling could save about 50% with half cost per tree if the plastic tubes are removed, compare to planting the nursery-grown seedlings.

8.2.4 Influence of differences between east and west coast

Apart from geomorphology difference, the influence from two monsoonal winds has caused different timing of rainy season between east and west coast of southern Thailand with similar amount of annual rainfall (1,800-1,900 mm), but not during the year of phenological observation (1,600-2,400 mm) (Chapter 2). Slightly different pattern of leafing between both sites, observed species leafed soon after partial leaf shedding in the early dry season at NST, while the flat and long peak was observed at KB, start from the beginning of the dry season till early rainy season. Based on frequency, the flowering pattern differed between east and west coast, sub-annual flowering, was dominant at NST, while annual flowering was more common at KB, accounting for about half of the total species in each site. However, different precipitation regimes did not markedly influenced reproductive phenology of observed species, except flowering duration, about 50% of total species lasted less than 1 month at KB but 1-2 months in NST. More open condition with higher degree of fragmentation might cause longer flowering period at NST, to attract pollinators as long as possible. Moreover, there were two peaks of fruit ripening at both sites, one during rainy season and a later during dry season, however two peaks of rainfall were observed at NST, and only during the first rain that ripening was high (Chapter 3).

In addition to annually different timing of wet season, period and intensity of rainfall from the long record (1989-2008) are likely different, there are 6 months of about 200 mm monthly rainfall and 6 months of less than 100 mm monthly in KB in dry season while there are 3 months of heavy rain (300-600 mm monthly) and about 100 mm monthly rainfall for rest of the year in NST. Hugely fluctuating rainfall with reduction or no rainfall at the end of season in NST was possibly the cause of significantly lower germination percentage in the field from late sowing, but continuing rainfall in KB was not.

There is heavy rain in the few months at the beginning of rainy season in NST. Thus, seeds with short dormancy should be suitable for direct seeding on the east coast to reduce the possibility of losing the seeds from leaching out before germination can take place. In contrast, the seeds with longer dormancy could be the candidates for sowing in KB because longer sufficient moisture during wet season. In addition, drought-tolerant species will give more chance for direct seeded plants to survive during 6 months of dry season with low monthly rainfall.

Fluctuating temperature and rainfall, and water-logging during wet season in NST might affect seedlings to grow slowly in the field. Although seeds were sown at the beginning of rainy season, the direct-seeded plants could not grow much better than nursery-grown seedlings at one year after sowing at NST, but they were capable at KB. Nevertheless, the direct seeded could grow significantly better than the nursery-raised plants at both sites at the end of 2nd rainy season after sowing. Mulching had reduced growth of seedlings in KB, because increased acidic condition when mulched with cut vegetations, and higher degree of compaction (Nussbaum et al., 1995; Woodward, 1996). Therefore, for any given reforestation site, the first step is to take soil samples for analysis and also do basic interview or literature review on land use history.

8.3 Patch dynamic after interventions on abandoned areas

Shortage of tree seeds is a major barrier for forest regeneration in an abandoned areas (Florentine & Westbrooke, 2004; Zimmerman et al., 2000), and it could be overcome by direct seeding in southern Thailand. Remnant forest trees could become potential seed source, particularly the species that bore ripe fruits at the beginning of rainy season, for recolonization in a disturbed patch and spatially dispersed among patches in the habitat. Seeds were buried, to protect them from desiccation and predation, and also to create suitable condition for their establishment. Early rainy season is the most suitable time for sowing the seeds, all species could germinate with no additional seed pretreatment required. About 80% of sown species could survive with varied recruitment success (10-40%) at 12 months, and averaged about 15% at 18 months after sowing. Seed and seedling predation, drought, and exhaustion of soil nutrients are not the factors which could delay or slow early regeneration in southern Thailand, as they were in several studies (Cubina & Aide, 2001; Garcia-Orth & Martínez-Ramos, 2008; Zimmerman et al., 2000) but competition from surrounding vegetations was. Thick weed cover can prevent the native species seed from reaching the soil, or compete for nutrients and moisture with newly recruited seedlings, however removing weeds prior to sowing and regular weeding during subsequent rainy season in the first two years after sowing could influence the excellent growth performance in year two after sowing.

Seed availability during early rainy season is a major part of the lottery hypothesis (Begon et al., 2006) or volleys of invasion and persistence (Pickett et al., 2001), which is important for restoration. Community dynamics may vary according to the order in which colonizing species happen to appear after a disturbance, and different disturbance sequences drove the microsms into different successional trajectories, sometimes leading to divergence in final community composition (Begon et al., 2006). To conserve the whole system, the community dynamic of patchy landscape has to be considered both in space and in time.

8.4 Limitations of this study and gaps in knowledge

The major limitations of this study are the small number of species and sites tested; species that dispersed the seeds during a few months prior to the rainy season are not equally diverse in seed traits, functional traits, and taxonomic relations (Chapter 4 and 7); only few species that bored fruits throughout the year in the study sites, therefore seed availability in both early and late sowing is the limitation for direct comparison on the effects of sowing times (Chapter 5). It is uncertain if the results are true at other sites with different conditions e.g. vegetation covers, microclimate, intensity of light and humidity. In addition, seedling growth and survival were monitoring only about 2 year after sowing, they are possibly change in subsequent years (Chapter 5 and 6).

Whist this study shows that seed traits and functional (e.g. dispersal mode) could be used to predict the suitability of species to be the candidate for direct seeding on degraded areas in southern Thailand, it does not explained the optimum amounts of seeds that should be sown for each sowing event. A further study on this should be conducted, as this would affect cost and early process of natural regeneration. A large scale field experiment in various successional processes to demonstrate the effectiveness of recommended species is also needed to convince the forestry officers and the public that this is a suitable and cost-effective technique for restoration in southern Thailand. Further study on what traits of seedling contribute to establishment success regarding taxonomic relations and ecological strategies should be conducted as to find out if it is possible to be used as a potential criteria for predict the suitable candidates. In addition, to promote direct seeding as the low cost technique, a degradable material to replace the PVC tubes for preventing seed lose should be investigated, importantly it should not affect the germination and too expensive.

Because growing concerns over global biodiversity loss and climate change have generated a recent surge in interest in the potential to restore tropical forest ecosystems, both for wildlife conservation and carbon storage, technique that use native species are required which are applicable on a large scale, with cost-effectiveness. Therefore, a special characteristic of candidate species (i.e. high carbon storage potential) should be further investigated regarding suitable regimes suggested from this study. Although there is an increasing concern for biodiversity, but it is not confer much on using native tree species in reforestation in southern Thailand. More understanding on importance of native species uses in the public, and more properly-designed planting trials on native species with adequate documentation are needed.

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Publications & Proceedings

List of Publication

1. **Tunjai, P.** and Elliott, S. (2011). Effects of seed traits on the success of direct seeding for restoring southern Thailand's lowland evergreen forest ecosystem. *New Forest* **(Revised)**

2. **Tunjai, P.** and Elliott, S. (201X). Phenology of lowland tropical tree species in southern Thailand. *Journal of Tropical Ecology* **(In preparation)**
3. **Tunjai, P.** and Elliott, S. (201X). Factors affecting the establishment and growth performance of direct-seeded seedlings. *Forest Ecology and Management* **(In preparation)**

List of Presentation

1. **Panitnard Tunjai**, Cherdsak Kuaraksa, Taweesak Polchoo, Theerasak Konghor and Stephen Elliott. 2009. Reproductive phenology in an evergreen seasonal forest: implication for forest restoration. ATBC – Asia Pacific Chapter Annual Meeting, Imperial Mae Ping Hotel, Chiang Mai, Thailand, February 12 – 15, **Oral Presentation.**
2. **Panitnard Tunjai**. 2010. Suitable seed traits for direct seeding to restore evergreen seasonal forest in southern Thailand. Student Conference on Conservation Science, hosted by National Centre for Biological Science, Bangalore, India, June 16 – 18, **Poster Presentation.**
3. **Panitnard Tunjai**. 2010. Planting the forest by direct seeding: an alternative way for ecological restoration. The 14th BRT Annual Meeting, Sunee Grand Hotel & Convention Center, Ubon Ratchathani, Thailand, October 10 – 12, **Oral Presentation.**
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