CHAPTER 5

Discussion and Conclusion

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

5.1 Determining Optimal Seed Storage Condition of Native Tree Species

Seed Storage Behaviour

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

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

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

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

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

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

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

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

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

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

Seed Storage Recommendations

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

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

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

* Seed storage behaviour not tested in this study.

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

Seed Biology

Seed Germination

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

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

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

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

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

Seed Dormancy

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

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

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

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

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

Germination

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

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

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

Dormancy

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

10th May, MT 3rd May and SP 17th July). In the field, moisture supply was sporadic unlike in the nursery, where water was applied daily.

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

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

Seedling Survival and Seedling Yield

In general, percent seedling survival and seedling yield (defined as percentage of survival seedling from total seed sown over one year), were not significantly different between the two sowing periods. *B. variegata* achieved the highest percent survival (69.7%) and seedling yield (60.7%). This species sown at collection time on 21st May had the highest percent germination (88.7%) and shortest dormancy (3.8 days). Seed size was 0.275 g which categorized the species as intermediate seed size (Doust, et al., 2006). Previous studies have shown that large or intermediate-sized seeds result in higher seedling survival (Tunjai and Elliott. 2012). *P. emblica* also exhibited high percent survival (51.1%) and had moderate seedling yield (22.1%) according to Tunjai and Elliott (2012). However, seed size of this species was small (0.024), the yield was relatively high (22.1%) compare to other studied species. *G. arborea* and *H. dulcis* had very low (less than 4%) survival while, *A. fraxinifolius* seedlings all died in the field. Small seed size often seems to predict failure of direct seeding (Tunjai and Elliott. 2012; Kuaraksa and Elliott. 2013). In addition, seedlings from small seeds had high risk in seed infection. For example, Kuaraksa and Elliott (2013) reported 90% mortality of *Ficus* spp. seedlings, due to damping-off disease. However, in this study, no relationships were found between seed size and seed germination, dormancy, seedling yield and growth. *G. arborea* and *H. dulcis* failed to establish by direct seeding in this study. In contrast, Tunjai (2005) reported very high percent survival *G. arborea* (more than 90%) after 2 years of monitoring and Pakkad (2005) reported similar results from *H. dulcis*, suggesting both species should be recommended for direct seeding. *A. lacucha*, a recalcitrant species, was only the species for which percent yield from immediately sown seeds was significant higher than for those from stored seeds.

Seedling Growth

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

Relative Species Performance Indices (RSPI's)

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

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

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

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

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

5.3 Comparing Direct Seeding with Conventional Tree Planting

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

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

5.4 Developing Treatments to Improve Direct Seeding

Hydrogel

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

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

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

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

Fertilizers

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

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

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

5.5 Applications for Automated Forest Restoration

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

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

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

Seed bombs or seed pellets effective function as “redesigned fruits” or dispersal units when employed in aerial seeding. The design of seed bombs/pellets should take into account soil hardness and texture, topography, seed characteristic and the constituents of the media of the pelleting materials or contained within the seed bombs. Seed projectiles should at least remain where they are dropped (for accurate spacing between seeding sites). Bombs can be designed with a sharp point to anchor the seeds in placed, whereas spherical pellets tend to roll around and accumulate in the lowest points of the landscape.

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

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

5.6 Conclusions

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

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

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

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

5.7 Recommendations

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

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

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

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