Journal of Tropical Forest Science 16(2): 248–259 (2004)

DIRECT SEEDING FOR FOREST RESTORATION ON ABANDONED AGRICULTURAL LAND IN NORTHERN THAILAND

K. Woods

Yale University, School of Forestry and Environmental Studies, 205 Prospect St., New Haven, CT 06511, United States of America. E-mail: kevin.woods@yale.edu

&

S. Elliott

Forest Restoration Research Unit (FORRU), Biology Department, Chiang Mai University, Chiang Mai 50200, Thailand

Received January 2003

WOODS, K. & ELLIOTT, S. 2004. Direct seeding for forest restoration on abandoned agricultural land in northern Thailand. Seed predation and desiccation present major limitations to the use of direct seeding as an efficient forest restoration technique. The study was designed based on the premise that scarifying seeds before sowing them in fields cleared of weeds would shorten seed dormancy to decrease the time available for seed predation to occur and that burial conceals seeds from potential predators. Therefore, the effects of four treatments (scarification, burial, application of mulch and scarification with burial) were tested on seed germination of four native forest tree species, sown in abandoned agricultural land in an upper watershed in Doi Suthep-Pui National Park, northern Thailand. The four tree species studied were *Sapindus rarak, Lithocarpus elegans, Spondias axillaris* and *Erythrina subumbrans.* Field tests showed that instead of rodents, ants were the seed predators. Scarification without burial did not accelerate seed germination in the field due to desiccation and severe predation by ants. Burial helped protect the seeds from predation as well as blocked direct sunlight and increased moisture retention, thus preventing desiccation of seeds. Seeds that benefit from scarification but which are susceptible to seed predation and desiccation should be scarified and buried to a depth twice the diameter of the seed (3–5 cm). For certain suitable species, this technique could offer an effective, cost-efficient alternative to outplanting nursery-raised seedlings for forest restoration projects, particularly in montane areas.

Key words: Seed predation – seed scarification – seed burial – mulch – seed germination

WOODS, K. & ELLIOTT, S. 2004. Penanaman terus biji benih untuk pemulihan hutan di tanah pertanian terbiar di utara negeri Thai. Serangan biji benih dan pengeringan mengehadkan penanaman terus biji benih sebagai teknik pemulihan hutan yang berkesan. Kajian ini dirancang berdasarkan kenyataan bahawa pelelasan biji benih sebelum penyemaian di lapangan yang bersih daripada rumpai dapat memendekkan kedormanan biji benih bagi mengurangkan masa yang ada untuk serangan biji benih. Kajian ini juga berdasarkan kenyataan bahawa penimbusan menyembunyikan biji benih daripada serangan haiwan berpotensi. Kesan keempat-empat rawatan (pelelasan, penimbusan, penggunaan sungkup dan pelelasan + penimbusan) terhadap percambahan biji benih empat spesies pokok hutan asli yang disemai di satu tanah pertanian yang terbiar di legeh di Taman Negara Doi Suthep-Pui di utara negeri Thai dikaji. Keempat-empat spesies yang dikaji ialah *Sapindus rarak, Lithocarpus elegans, Spondias axillaris* dan *Erythrina subumbrans.* Kerja lapangan mendapati semut merupakan perosak biji benih dan bukan roden. Pelelasan tanpa penimbusan tidak mempercepat percambahan biji benih di lapangan disebabkan pengeringan dan serangan yang teruk daripada semut. Penimbusan dapat melindungi biji benih daripada haiwan dan daripada cahaya matahari terik. Oleh itu, lembapan dapat dibendung dan seterusnya ini menghindari pengeringan biji benih. Biji benih yang mendapat manfaat daripada pelelasan tetapi rentan terhadap serangan haiwan dan pengeringan patut dilelas dan ditimbus pada kedalaman dua kali diameter biji benih (3–5 cm). Bagi beberapa spesies yang sesuai, teknik ini merupakan pilihan yang berkesan dan menjimatkan kos untuk projek pemulihan hutan, khasnya di kawasan bergunung, berbanding menanam biji benih yang dibesarkan di tapak semaian.

Introduction

Deforestation and the degradation of tropical forests and soils have reached unprecedented levels because of the increasing need for agricultural land and the intensified use of forest resources. The Food and Agriculture Organization (FAO) reported that the area of natural tropical forest cover (canopy cover >10%, not including plantations) declined from 1945 to 1803 million ha from 1990 to 2000. The net annual average reduction in natural tropical forest cover was 14.2 million ha (approx. 0.7% year^{-1}). In Thailand, natural forests covered 9.8 million ha in 2000 (19.3% of country's area). Despite a commercial logging ban since 1989, the average annual reduction in natural forest cover (1995–2000) remained at 0.26 million ha (2.3% of the 1995 forest cover figure) (FAO 2001). Overall, since 1961, Thailand has lost nearly two-thirds of its forests (Bhumibamon 1986).

The concomitant loss of biodiversity, ecosystem services such as water retention, erosion control and carbon storage, and disturbance of biotic and abiotic cycles have challenged rural communities' livelihoods and threatened remaining natural resources. Although countries are now attempting to solve the problem by protecting remaining forests, such forests are often too degraded and depleted to achieve conservation objectives. Therefore, natural regeneration must often be accelerated to convert degraded land into healthy natural forest (Hardwick *et al.* 2000). Most forest restoration projects involve planting nursery-raised tree seedlings, but this is the most labour- and capital-intensive method of forest restoration. Seed collection, raising seedlings in a nursery, planting and maintaining planted saplings until they can establish and become independent all require substantial labour inputs (Hardwick *et al.* 2000). Furthermore, root deformities caused by seedlings outgrowing their containers and those caused by careless transplanting techniques can reduce sapling survival in the field (Zangkum 1998).

These disadvantages prompted the investigation into the possibility of using direct seeding as a cost-efficient, low technology, community-based alternative to using nursery-raised seedlings for forest restoration. There are few reported cases in the tropics of direct seeding having been successfully implemented, on a large scale, to restore degraded forest lands (Sun & Dickinson 1995). Reasons for failure are attributed to seed predation in cleared areas significantly limiting seed germination, with mortality levels ranging from 20% (Osunkoya 1994) to 100% (Hau 1997). Levels of post-dispersal seed predation vary greatly among species (Mittelbach & Gross 1984, Willson & Whelan 1990, Hulme 1994, Osunkoya 1994, Hau 1997). This indicates that it may be possible to identify seed characteristics favourable for successful direct seeding and thus infer a general basis by which to choose species for this method of forest restoration (see Knowles & Parrotta 1995). The aims of this study were, therefore, to assess which tree species might be most suitable for direct seeding and to test the effectiveness of seed scarification, burial and mulch application in increasing seed germination per cent and rate in the severe climatic and edaphic conditions prevalent in open, degraded forest.

Seed scarification has been used in previous studies to accelerate germination (Clemens 1980, Snell & Brooks 1998), but few studies employed this technique to prevent seed predation (Sun & Dickinson 1995). Vanderwoude (1995) commented that direct seeding is constrained by the need for adequate soil moisture and effective weed control. Clemens (1980) suggested using an organic mulch to retain moisture, while Sun and Dickinson (1995) recommended burying seeds for moisture retention as well as protection from ants. Hau (1999) showed that half-buried seeds did not reduce seed predation.

Direct seeding is potentially of greatest use where establishment costs are more important than growth rates. Direct seeding could significantly reduce the cost of planting seedlings because labour and time for raising seedlings in nurseries are not required. If this technique can be proven to be operationally efficient, it may be particularly useful for steep slopes or otherwise inaccessible areas, where transportation of seedlings is difficult, as well as for rural montane communities with limited funding and other resources to establish and manage tree nurseries.

Materials and methods

Study sites

All nursery experiments were conducted at the Forest Restoration Research Unit (FORRU) tree nursery, located at the headquarters of Doi Suthep-Pui National Park, northern Thailand (18° 50' N, 98° 50' E) at 1000 m elevation, in a transitional zone between mixed evergreen + deciduous forests and primary evergreen forest (Maxwell & Elliott 2001). The area experiences a monsoonal climate, with a marked dry season from December to April, when monthly rainfall is usually less than 50 mm, followed by a rainy season, which peaks in August. Annual rainfall is usually about 1000 mm at the base of the mountain and about 2000 mm near the summit (1685 m elevation). There is a cool season from November to February, during which mean daily temperatures are 20.2–24.2 °C, after which temperatures rise sharply, peaking at about 30 °C in April.

Field trials were carried out in three experimental plots established in the north of Doi Suthep-Pui National Park, in a degraded watershed (18° 52' N, 98°

49' E) at 1207–1310 m elevation. The location of the plots was decided in collaboration with FORRU and the villagers of Ban Mae Sa Mai, a Hmong hill tribe community about 2 km below the plots. Originally the area had been covered in evergreen forest, but the forest had been cleared approximately 20 years previously and the area cultivated for cabbages, corn, potatoes and fruit trees. Fires, degraded soil and weeds had prevented forest regeneration. Although scattered mature trees remain, the area is now largely dominated by weedy herbaceous vegetation such as *Pteridium aquilinum* (Dennstaedtiaceae), *Bidens pilosa* var. *minor, Ageratum conyzoides, Eupatorium odoratum* and *E. adenophorum* (all Compositae), *Commelina diffusa* (Commelinaceae), *Imperata cylindrica* var. *major* and *Thysanolaena latifolia* (both Gramineae).

Species studied

Four potential tree species were chosen for this study from a list of proven successful tree species which excelled in the field, based on past FORRU experiments (Elliott *et al.* 2003). Final species selection was based on fruit available at time of sowing, high germination per cent and rate, potential for pretreatment success and fast seedling growth rate. Table 1 lists the selected four species and their characteristics: *Sapindus rarak, Lithocarpus elegans, Spondias axillaris* and *Erythrina subumbrans.*

Sapindus rarak (Sapindaceae) is an uncommon, fast-growing, medium-sized, deciduous tree, up to 25 m tall, diameter breast height (DBH) up to 25 cm. Its habitat includes mixed evergreen + deciduous and primary evergreen seasonal forest, often in disturbed areas; elevation 615–1620 m. The drupe contains only one globuse, dull black seed, 16.4 × 15.9 × 15.1 mm; dispersed by animals.

Lithocarpus elegans (Fagaceae) is a very common evergreen tree, up to 25 m tall. It grows in bamboo-deciduous, mixed evergreen + deciduous and primary evergreen forest with pine; elevation 450 to 1450 m. Each dark glossy brown nut contains one subglobose seed, 10.4 × 9.3 × 7.9 mm; dispersed by animals.

Spondias axillaris (Anacardiaceae) is a fairly common, medium-sized, deciduous tree, up to 25 m tall, DBH up to 50 cm. Its habitat is evergreen forest both with and without pine, often in degraded areas; elevation 700–1600 m. Each drupe contains a solitary, obovoid pyrene with 4–5 depressions, each depression with a single, oblong, flattened, brown seed, 17.0 × 14.3 × 13.7 mm; dispersed by animals.

Erythrina subumbrans (Leguminosae, Papilionoideae) is a common, medium-sized, fast-growing, deciduous tree, up to 25 m tall, DBH up to 86 cm. It is found in bamboo-deciduous, mixed evergreen + deciduous and primary evergreen seasonal forest, especially in degraded areas and along stream valleys at lower elevations; elevation usually 400–1250 m. Each pod contains 1–4 dark brown, mostly ellipsoid and kidney-shaped seeds, 9–16 × 7–11 × 7–9 mm; dispersed by wind.

Seed collection and storage

All fruits were collected from trees within Doi Suthep-Pui National Park (Table 1). Fruits were stored at the FORRU nursery in open plastic bags out of

Table 1 Seed characteristics

Species	Seed size[a]	Seed coat hardness	Orthodox/ Recalcitrant	Dispersal
Sapindus rarak	Large	Hard	Orthodox	Animal
Lithocarpus elegans	Medium	Hard	Orthodox	Animal
Spondias axillaries	Large	Hard	Orthodox	Animal
Erythrina subumbrans	Medium	Soft	Recalcitrant	Wind

[a] Small (< 5 mm), medium (5 < x < 10 mm), large (>10 mm)

direct sunlight for one to two days until seeds were extracted. For all species, fruit pulp was removed and the seeds rinsed with water. Seeds were then spread out on paper and air dried in shade overnight.

After one night of air drying, seeds were stored (approximately one week for *L. elegans, S. axillaris* and *S. rarak,* and 1.5 months for *E. subumbrans*) in airtight jars at the FORRU nursery while awaiting field and nursery trials. All jars were stored at room temperature (26–28 °C) out of direct sunlight.

Germination trials in the nursery

Experiments in the nursery tested the effects of mechanical scarification on seed germination. Scarification was done by splitting open the seed coat using scissors or a sharp knife to enable water to be absorbed into the embryo and trigger germination.

Seeds were sown in modular plastic trays in partial shade (about 40% of full sunlight), placed on top of concrete benches under a semi-transparent plastic roof. A total of 72 seeds were divided into three replicate batches of 24, each randomly assigned to different benches and watered daily. Each replicate consisted of 24 adjacent modules (3.5 × 3 × 7 cm) in one seed tray. The germination medium consisted of two parts forest soil mixed with one part coconut husk and one part peanut husk. At weekly intervals, seed germination was monitored, recording date and location of all germinated seeds. Seeds were sown in the nursery at the same time as in the field to compare germination under nursery conditions versus germination in the field with limiting factors.

Germination was defined as the appearance of any part of the hypocotyl above the soil surface. Median length of dormancy (MLD), the time to germination of the median seed, was used to quantify germination rate. MLD was calculated for each replicate and averaged. The median length of dormancy was used in order to eliminate the effects of a few outlying seeds, with unusually long dormancy periods, which distorted the mean.

Germination trials in the field

Cages, measuring 50 × 35 × 20 cm, were constructed using wire mesh (2.2 × 2.2 cm) (Sharp 1995) to exclude rodent seed predators. The experimental design consisted of three blocks (each with two replicates), comprising both caged and non-caged treatments per block. The blocks were constructed by first removing weeds and then digging holes measuring 75 × 50 × 15 cm for both the caged and non-caged treatments. Cages were placed in the holes for each of the caged treatments. The soil was replaced up to the ground level. The cages were closed with a lid measuring 50 × 45 cm. All replicates were bordered on one side by tall weeds. A control and four treatments (scarification, burial, mulch and scarification-with-burial) were tested in both caged and non-caged plots in both replicates within each block. Seeds for the controls were placed directly on top of exposed soil. For the scarification treatment, scarified seeds were also placed directly on exposed soil. Seeds for the burial and scarification-with-burial treatments were buried twice the diameter of the seed. Seeds for the mulch treatment were placed on top of bare soil and covered by 10 cm of cut weeds.

For each treatment, except scarification-with-burial, the following numbers of seeds were sown per replicated block (caged and non-caged pooled together) per treatment: *S. rarak,* 20 seeds; *L. elegans,* 40 seeds; *S. axillaris,* 40 seeds and *E. subumbrans,* 20 seeds. For the scarification-with-burial treatment, only one species was tested, according to seed availability: *S. axillaris,* 10 seeds.

Seed germination and predation were monitored daily for the first few days, then twice per week for 60 days, until conclusion of the experiment. A seed was counted as having germinated when any part of the hypocotyl became visible above the soil surface. To mimic natural conditions, litter was not removed during monitoring. When counting the number of germinating seeds for *S. axillaris,* all stems emerging from a single pyrene were counted as only one seedling.

Data analysis and interpretation

Germination in the nursery was compared with that in the field. The nursery control was compared to the buried treatment in the field, since both were non-scarified and buried. The scarified treatment in the nursery was compared to the scarified treatment in the field, except for *S. axillaris,* where the scarification-with-burial treatment was used for the comparison. Each of the three replicated blocks (positioned in three different plots 0.5 km apart) consisted of two replicated sets of caged and non-caged treatments. Since no rodent seed predation was observed, the cages had no effect on germination success. Therefore, data from each set of the caged and non-caged treatments (both replicates) in each block were combined to make three replicated blocks. Consequently, the final mean germination per cent and MLD for each species is the mean of the three replicated blocks.

To detect significant differences in seed germination between the control and scarification treatment in the nursery, two statistical tests were applied. To determine if germination rate was significantly different between the treatments in the nursery, the Kolmogorov-Smirnoff two-sample test was used with $p \leq 0.05$ (Sokal & Rohlf 1981). To test if the final germination percentage was significantly different between the two treatments in the nursery, the Chi-squared test was applied using a 2 × 2 contingency table and $p \leq 0.05$ (Sokal & Rohlf 1981). One-way ANOVA and paired *t*-tests were applied to detect if germination per cent and rate significantly differed between treatments in the field (Sokal & Rohlf 1981).

Results

The assertion that seed predation by rodents is a major factor limiting seed survival in deforested areas was not supported by this study, since no such predation was observed. However, ants were observed predating the seeds. Nevertheless, seed predation by ants could not be quantified since the experimental design only tested seed predation by rodents. Cages had no effect either on seed removal or on germination success since the mesh cages did not prevent seed predation by ants.

Furthermore, the hypothesis that scarification shortened the time period during which seed predation might occur in the field by accelerating germination was also not supported by the data, as shown in Table 2. Scarification significantly accelerated germination (MLD) of *S. rarak* seeds in the nursery. However, scarified *S. rarak* seeds in the field achieved a significantly lower per cent germination as compared with the nursery trial. Scarification significantly reduced per cent germination of *L. elegans* seeds in both the nursery and field trials.

Table 2 Summarised nursery and field mean germination per cent and median length of dormancy (MLD)

Species	Treatment	Nursery germ %	Nursery MLD (days)	Field germ %	Field MLD (days)
Sapindus rarak	Control	59 a (13)	55 b (12)	11 b (12)	62 b (2)
	Scarification	62 a (17)	30 a (6)	18 b (24)	40 b (5)
	Burial	–	–	58 a (13)	35 a (2)
	Mulching	–	–	37 ab (8)	48 ab (18)
Lithocarpus elegans	Control	68 a (16)	37 a (7)	31 b (25)	47 b (7)
	Scarification	10 b (4)	30 a (10)	4 c (8)	43 b (11
	Burial	–	–	73 a (3)	32 ab (9)
	Mulching	–	–	58 a (4)	27 a (4)
Spondias axillaris	Control	33 a (9)	141 a (32)	21 b (8)	61 c (4)
	Scarification	42 a (15)	99 a (26)	9 b (8)	61 c (4)
	Burial	–	–	57 a (10)	50 b (7)
	Mulching	–	–	21 b (20)	57 bc (2)
	Scar/Burial	–	–	50 a (10)	38 a (5)
Erythrina subumbrans	Control	7(3)	20(5)	0 b	–
	Scarification	0	–	0 b	–
	Burial	–	–	10 a (5)	21 a (5)
	Mulching	–	–	3 b (3)	19 a (0)

Values are means of three replicates with standard deviations in parentheses.

Within species, values in the same column followed by the same letter are not significantly different.

For per cent germination in the nursery, Chi-squared test was used; for per cent germination and MLD in the field, ANOVA and paired t-tests were used at the 0.05 probability level.

MLD = median length of dormancy

"–" = represents no test conducted for germination and therefore not able to calculate MLD, "0" represents attempted but failed germination test.

Note: Control nursery treatment was compared to burial field treatment.

Burial substantially increased germination success in the field (Table 2). Compared to the field control, it significantly accelerated germination (MLD) of *S. rarak* and *S. axillaris* seeds and significantly increased germination percentage for all species in the field. Burial significantly decreased field MLD for *S. rarak* ($p < 0.01$) and *S. axillaris* ($p < 0.01$) compared with the nursery trials. Burial also significantly increased germination percentage for *S. axillaris* in the field compared with the nursery trials ($p < 0.05$). Burying scarified *S. axillaris* seeds in the field achieved a significantly high germination per cent as well as produced a significantly lower MLD compared with the nursery ($p < 0.01$) and compared with the other *S. axillaris* field treatments.

Mulching had less influence on improving germination success. Compared with the control, mulching had significantly increased both germination rate and per cent of *L. elegans* seeds but had no significant effect on other species.

Across all species in the field, burial as well as scarification-with-burial resulted in significantly higher mean germination per cent, although not significantly higher than the mulch treatment (Table 3). The burial, mulch and scarification-with-burial treatments in the field resulted in significantly faster germination rates than the control or scarification treatments, although not significantly different.

Stored *E. subumbrans* seeds failed to germinate in the nursery, although fresh seeds before storage achieved good germination results. In the nursery, seeds were attacked by ants and fungal infection. In the field, however, a few seeds germinated in both burial and mulch treatments, with the burial treatment achieving significantly highest germination per cent.

Discussion

Despite previously published evidence of intense seed predation by rodents in a small forest clearing in Doi Suthep-Pui National Park (Sharp 1995) as well as other direct seeding experiments in other similarly degraded montane environments (Hau 1997), ants were the only seed predators observed. Ants attacked the scarified, unburied seeds, although some of the control seeds (non-scarified) were also attacked. Very few seeds in the burial or mulch treatments were predated by ants. The abundance of ants might be due to the absence of weeds, since ants are more prevalent in open habitats, whereas rodents generally forage in vegetation that provides protective cover (Schupp 1988, Manson & Stiles 1998).

Table 3 Overall field mean germination and mean length of dormancy (MLD) across species

Overall mean across species	Control	Scarification	Burial	Mulching	Scar/Burial
% Germination	16 bc (17)	8 c (13)	50 a (26)	30 ab (23)	50 a (10)
MLD (days)	56 b (9)	57 b (8)	34 a (11)	39 a (18)	38 a (5)

Values are the means of three replicates with standard deviations in parentheses.

Within species, values in the same column followed by the same letter are not significantly different.

MLD = mean length of dormancy

For per cent germination and MLD in the field, ANOVA and paired *t*-tests were used.

Unlike in the nursery, scarified *S. rarak* seeds in the field did not perform better than the control probably because the split testa exposed the embryo to direct sunlight. Buried untreated *S. rarak* seeds in the field attained a similar germination per cent as control seeds in the nursery, as well as a significantly lower MLD. Since scarification accelerated germination in the nursery, it is speculated that scarified *S. rarak* seeds buried in the field would be protected from direct sunlight and achieve a synchronised, earlier germination peak. If seedling survival is not jeopardised by direct seeding, then sowing buried scarified *S. rarak* seeds in areas cleared of weeds offers a viable alternative to planting nursery-grown seedlings.

Lithocarpus elegans control seeds in the field appeared visibly desiccated due to exposure to direct sunlight. Burial in the field achieved a similar per cent germination and MLD as those of the control nursery experiment. Svasti (2000) reported that Fagaceae seedlings derived from direct seeding have a higher survival rate, compared with nursery-raised seedlings, because taproots tend to break through the seedling containers and get damaged. Therefore, the data strongly support fully burying non-scarified *L. elegans* seeds in areas cleared of weeds if early seedling survival in the field from direct seeding is not hampered compared with transplanting seedlings raised in nurseries.

The significantly lower MLD of non-scarified *S. axillaris* pyrenes sown in the field compared with the nursery could be due to direct sunlight cracking the pyrene, thus breaking imposed dormancy. Exposed scarified pyrenes in the field suffered reduced germination success due to observed predation by ants. Burying pyrenes improved germination per cent and rate, probably from deterring predation and increasing moisture availability. Scarified pyrenes in the field attained significantly lowest MLD if they were buried. In fact, scarification-with-burial, under field conditions, resulted in better germination success than in nursery conditions. This species has poor root development when grown in plastic bags in the nursery and suffers further damage during transplantation (pers. observation). Therefore, burying scarified pyrenes in the field is probably a more effective method to establish *S. axillaris* seedlings on degraded land than transplantation of nursery-raised seedlings.

Erythrina subumbrans seeds were attacked by ants and fungi both in the field and in the nursery. It was observed that seeds buried or covered by mulch were better able to escape seed predation by ants than those sown on exposed soil. Therefore, burial of non-scarified seeds with fungicide applied may enable direct seeding of this species in forest restoration projects. Also, the very low MLD would allow the germinating seedlings of this species more time to outgrow competing herbaceous weeds. The low seed viability was probably due to improper storage (for example, refrigeration was not used) and this reflects the challenges of using recalcitrant seeds for forest restoration projects. Seeds should be sown in the field immediately after fruit collection if possible, especially for recalcitrant seeds, so that seed storage is not needed or its duration is minimised. Further research is needed on proper seed storage and desiccation of orthodox seeds to ensure high seed viability for direct seeding projects. In order to minimise seed storage, species selected for direct seeding should fruit at the beginning of the rainy season when direct seeding is most likely to be successful.

Burying scarified seeds could improve germination by blocking direct sunlight and heat, maintaining a humid micro-climate (which could allow drought-resistant species to be used) and concealing seeds from potential predators (Sun & Dickinson 1995). If seeds benefit from scarification in the nursery then they should be scarified and fully buried in areas cleared of weeds for direct seeding. However, this should only be done if scarification significantly improves germination, as seed scarification is labour intensive and could actually increase desiccation and encourage seed predation.

Seeds that are covered by soil or cut vegetation in the field will germinate faster than if scattered on the soil surface, as supported by the data presented in Table 2. However, it was observed that mulch suppressed seedling growth and was not as effective in maintaining a moist micro-habitat as the burial treatment. Sowing seeds into weedy vegetation would provide cover from direct sunlight, but higher rodent density in weeds may contribute to increased rodent seed predation (Schupp 1988, Manson & Stiles 1998). In addition, any resulting seedlings would be disadvantaged by competition from weeds (Sun & Dickinson1996).

Rapid germination and high germination per cent as well as rapid seedling growth in the field are the main criteria that determine whether or not a species is suitable for direct seeding (Pakkad *et al.* 2003). A low MLD would allow seeds to better compete with weeds by giving more time for growth before the rainy season is over. It also reduces the period when seeds are at risk of being predated, although most predation occurs within the first few days after sowing (pers. observation). A high germination per cent would increase the efficiency of direct seeding since fewer seeds would need to be sown.

It is suggested that future experiments compare seedling field survival after germination between nursery-raised and direct-seeded seedlings. The recommendation for direct seeding depends on sufficient growth rates of direct-seeded seedlings. This is of particular concern since past experiments have shown that the growth of direct sown trees can be slower than planted seedlings (Vanderwoude *et al.* 1996). Research could also focus on the potential of using direct seeding for enrichment planting under a semi-closed canopy. More investigation should focus on the selection of suitable fungicides and ant-and-rodent repellents, which are hydrophobic, cheap, non-toxic and widely available. Vanderwoude (1995) suggested pelleting seeds with lime to reduce harvesting by ants.

Direct seeding is particularly recommended when rural communities are planting on steep hill sides, are less concerned about seedling growth rates, have available labour for field maintenance, and lack resources for establishing tree nurseries.

Acknowledgments

The authors are grateful to FORRU at Chiang Mai University for institutional support. This experiment had continual guidance from the staff at FORRU, especially P. Navakitbumrung, C. Kuarak, R. Punyayod, G. Pakkad, T. Seethong and J. Bunyadit. R. Scott and B. Jensen were particularly helpful in assisting in field preparation. N. Jitlan helped monitor seed germination in the nursery. The authors also thank Doi Suthep-Pui National Park authorities for permission to work in the park. This research was financially supported by a Fulbright Student Research Grant, with administrative support from the Thailand-United States Education Foundation (TUSEF).

References

Bhumibamon, S. 1986. *The Environment and Socio-economic Aspects of Tropical Deforestation: A Case Study of Thailand.* Kasetsart University, Bangkok.

Clemens, J. 1980. Direct seeding of native woody plants. *Landscape Australia* 4/80: 279–284.

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

FAO (Food & Agriculture Organization). 2001. *State of the World's Forests 2001.* FAO, Rome.

Hardwick, K., Healey, J. & Blakesley, D. 2000. Research needs for the ecology of natural regeneration of seasonally dry tropical forests in Southeast Asia. Pp. 165–180 in Elliott, S. *et al.* (Eds.) *Forest Restoration for Wildlife Conservation.* International Tropical Timber Organisation and Chiang Mai University, Chiang Mai.

Hau, C. 1997. Tree seed predation on degraded hillsides in Hong Kong. *Forest Ecology and Management* 99: 215–221.

Hau, C. 1999. The establishment and survival of native trees on degraded hillside in Hong Kong. Ph.D. thesis, University of Hong Kong, Hong Kong.

Hulme, P. 1994. Post dispersal seed predation in grassland: its magnitude and source of variation. *Journal of Ecology* 84: 853–861.

Knowles, O. & Parrotta, J. 1995. Amazonian forest restoration: an innovative system for native species selection based on phenological data and field performance indices. *Commonwealth Forestry Review* 74(3): 230–243.

Manson, R. H. & Stiles, E. W. 1998. Links between microhabitat preferences and seed predation by small mammals in old fields. *Oikos* 82: 37–50.

Maxwell, J. F. & Elliott, S. 2001. *Vegetation and Vascular Flora of Doi Sutep-Pui National Park, Chiang Mai Province, Thailand.* Thai Studies in Biodiversity 5. Biodiversity Research and Training Programme, Bangkok.

Mittelbach, G. & Gross, K. 1984. Experimental studies of seed predation in old fields. *Oecologia* 65: 7–13.

Osunkoya, O. 1994. Postdispersal survivorship of north Queensland rainforest seed and fruits: effects of forest, habitat, and species. *Australian Journal of Ecology* 19: 52–64.

Pakkad, G., Torre, F., Elliott, S. & Blakesley, D. 2003. Selecting seed trees for a forest restoration program: a case study using *Spondias axillaris* Roxb. (Anacardiaceae). *Forest Ecology and Management* 182: 363–370.

Schupp, E. 1988. Seed and early seedling predation in the forest understory and in treefall gaps. *Oikos* 51: 71–78.

Sharp, A. 1995. Seed predation on degraded agricultural watersheds at Ban Mae Sa Mai, northern Thailand. M.Sc. thesis, Chiang Mai.

Snell, A. & Brooks, S. 1998. Direct seeding as a method of revegetating degraded land. Pp. 232–235 in *Proceedings from Managing and Growing Trees: Farm Forestry and Vegetation Management Training Conference.* 19–21 October 1998. Queensland.

Sokal, R. & Rohlf, F. 1981. *Biometry.* Second edition. W. H. Freeman, New York.

Sun, D. & Dickinson, G. 1995. Direct seeding for rehabilitation of degraded lands in north-east Queensland. *Australian Journal of Soil and Water Conservation* 8(4): 14–17.

Sun, D. & Dickinson, G. 1996. The competition effect of *Brachiaria decumbens* on the early growth of direct seeded trees of *Alphitonia petriei* in tropical north Australia. *Biotropica* 28(2): 272–276.

Svasti, M. R. S. 2000. Rivers in jeopardy: a village community's response to the destruction of their upper watershed forests in the Mae Soi valley catchment, northern Thailand. Pp. 123–134 in Elliott, S. *et al.* (Eds.) *Forest Restoration for Wildlife Conservation.* International Tropical Timber Organisation and Chiang Mai University, Chiang Mai.

Vanderwoude, C. 1995. Protection of seed from harvesting by ants: a study of direct weeding of four native tree species in south-east Queensland. Honours thesis. Charles Sturt University, Albury.

Vanderwoude, C., Pickersgill, G. & Dickinson, G. R. 1996. The efficacy of direct seeding as a revegetation strategy for humid and sub-humid areas of Queensland. Paper presented at the Managing and Growing Trees Training Conference. 8–10 October 1996. Bundaberg.

Willson, M. & Whelan. 1990. Variation in post-dispersal survival of vertebrate-dispersed seeds: effects of density, habitat, location, season, and species. *Oikos* 57: 191–198.

Zangkum, S. 1998. Growing tree seedlings to restore forests: effects of container type and media on seedling growth and morphology. M.Sc. thesis, Chiang Mai University, Chiang Mai.