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Selecting framework tree species for restoring seasonally dry tropical forests in northern Thailand based on field performance

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Abstract

Framework tree species are indigenous forest tree species, planted to complement and accelerate natural regeneration of forest ecosystems and encourage biodiversity recovery, on degraded sites. In this paper we test the extent to which 37 native forest tree species might act as framework tree species to accelerate recovery of evergreen, seasonal forest in a degraded upper watershed in Doi Suthep-Pui National Park in northern Thailand. The trees were planted at a density of 3125 ha^{-1} in 1998 and 1999. The plots were hand weeded, and fertiliser applied around planted trees three times during the rainy season. Field performance of planted trees was assessed at the end of the second wet season after planting by monitoring height, crown width and weed cover. A fire, which spread through some of the plots in March 2001, enabled assessment of resilience to fire for some of the species. Nine species were ranked as 'excellent' framework species, including *Ficus hispida* var. *hispida*, *Gmelina arborea*, *Hovenia dulcis*, *Melia toosendan*, *Michelia baillonii*, *Prunus cerasoides*, *Rhus rhetsoides* and *Spondias axillaris*. Fifteen species qualified as 'acceptable' framework species: *Acrocarpus fraxinifolius*, *Balakata baccata*, *Castanopsis acuminatissima*, *Ficus altissima*, *Ficus benjamina* var. *benjamina*, *Ficus glaberrima* var. *glaberrima*, *Ficus racemosa* var. *racemosa*, *Ficus subulata* var. *subulata*, *Glochidion kerrii*, *Heynea trijuga*, *Macaranga denticulata*, *Machilus bombycina*, *Nyssa javanica*, *Sapindus rarak* and *Sarcosperma arboreum*. Only four species were ranked as 'marginal': *Bischofia javanica*, *Ficus heteropleura* var. *heteropleura*, *Manglietia garrettii* and *Quercus semiserrata*. Nine species performed poorly in most respects and should probably be rejected as framework species: *Aglaia lawii*, *Callicarpa arborea* var. *arborea*, *Cinnamomum caudatum*, *Diospyros glandulosa*, *Helicia nilagirica*, *Horsfieldia thorelii*, *Lithocarpus fenestratus*, *Phoebe cathia* and *Pterocarpus macrocarpus*.

Keywords: Framework species; Tropical forest restoration; Species selection; Seedling performance

1. Introduction

In Thailand, as in most tropical countries, deforestation and forest degradation are widely recognised as major threats to environmental stability, economic prosperity and social welfare, particularly amongst rural communities. Remaining forest has become fragmented into patches that are incapable of supporting viable populations of many species, especially large vertebrates and out-crossing trees (Lynam, 1997). In the northern highlands, which constitute the country's most important watershed, large areas

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of degraded forestland require urgent reforestation. In areas earmarked for economic forestry, conventional reforestation with monoculture plantations (mostly pines and eucalyptus) will remain important. However, a fresh approach is needed to restore forest ecosystems within conservation areas, where biodiversity is the top management priority.

One of the measures implemented by the Government of Thailand to stem forest degradation has been the creation of an extensive system of protected areas. Since the early 1960s, the Royal Forest Department (RFD) has declared 138 national parks or wildlife sanctuaries, covering more than 15% of the country (Elliott and Cubitt, 2001). However, these conservation areas often contain extensive degraded sites, formerly cleared by logging or to provide land for agriculture. If such sites are to fulfil their statutory function of biodiversity conservation, they should be planted with indigenous forest tree species to restore original forest ecosystems wherever possible. Such tree planting should aim to complement natural forest regeneration rather than replace it. Although it is impractical to plant all tree species that may once have been present, it is possible to restore the levels of tree species richness, ecosystem structure and ecological functioning, of the original forest ecosystem. This is a highly specialised form of reforestation termed 'forest restoration', to distinguish it from other forms, such as monoculture plantations, agro-forestry and so on (Elliott, 2000). With an abrupt change in reforestation policy in 1993, the RFD launched a project to replant 8273 km^2 of degraded forest land nation-wide with native forest tree species, to celebrate His Majesty King Bhumibol Adulyadej's Golden Jubilee. The project aimed to use a wide range of native forest tree species and planted areas were to remain as forest in perpetuity. However, implementing such an ambitious project was considerably constrained by ignorance of how to grow and plant the wide range of native tree species needed.

One method of forest restoration that has proved very successful in Queensland, Australia, is the so-called 'framework species method' (Goosem and Tucker, 1995; Lamb et al., 1997; Tucker and Murphy, 1997; Tucker, 2000), which involves planting mixtures of 20–30 both pioneer and climax tree species in a single step. Essential characteristics of framework species are: (i) high field performance (high survival and growth rates) in open degraded sites; (ii) spreading, dense crowns that shade out herbaceous weeds and (iii) provision of resources that attract seed-dispersing wildlife (e.g. fruits, nectar, nesting sites, etc.) at an early age (Goosem and Tucker, 1995). Fire is a serious annual hazard to tree establishment in seasonally dry tropical climates, so an ability to resist or recover after fire is also a regionally important characteristic of framework species. Furthermore, framework species should be easily propagated in nurseries, with features such as reliable seed availability, rapid and synchronous germination and growth of seedlings to a plantable size (50–60 cm) in less than 1 year (FORRU, 1998).

Planted framework trees 'capture' the site, re-establish a multi-layered forest canopy and restore forest productivity and nutrient cycles. Animals, attracted by the planted trees, disperse available seeds of many other (non-planted) trees into planted areas. Furthermore, the planted trees modify the microclimate and create weed-free conditions, which favour germination and natural establishment of forest tree seedlings. Seeds produced by the planted framework species are also dispersed into surrounding degraded areas, so that planted framework trees can act as a "nucleus" for forest restoration over a broader scale in a degraded landscape. Propagation of framework species in nurseries for northern Thailand has already been covered in Blakesley et al. (2002) and Elliott et al. (2002). The present paper focuses on field performance.

In Queensland, the success of the framework species method has been clearly demonstrated. Tucker and Murphy (1997) reported that framework species plots, under various site conditions, became colonised by 15–49 naturally establishing tree species within 5–7 years of planting. An important question is: can the principles of the framework species method be successfully applied to restore tropical forest ecosystems elsewhere? Goosem and Tucker (1995) outlined some of the required characteristics of framework tree species and published separate lists of suitable species for planting in the 12 ecological mapping units of the Queensland Wet Tropics World Heritage Area (defined by altitude, climate and geology). However, no data quantifying the extent to which the listed species met the specified criteria were presented.

Since 1994, the Forest Restoration Research Unit (FORRU) of Chiang Mai University has been assessing the suitability of the framework species approach for restoring evergreen, seasonal forest (EGF) (sensu Maxwell and Elliott, 2001) on degraded land in the highlands of northern Thailand (FORRU, 1998, 2000). Selecting candidate framework species for the field trials described in this paper required extensive background studies. Germination trials and monitoring of early seedling growth were carried out on 400 tree species, indigenous to Doi Suthep-Pui National Park, where FORRU is located. Phenology and fruit characteristics of more than 100 species were recorded (Pakkad et al., 1999). Studies of seedling growth in the nursery enabled compilation of species production schedules (Kuarak et al., 2000; Elliott et al., 2002; Blakesley et al., 2000, 2002), whilst pilot planting trials in 1995–1997 enabled identification of some species likely to perform well in degraded sites.

Based on these studies, we established trial plots in 1998 and 1999 to test 37 candidate framework tree species in a degraded watershed area in the north of Doi Suthep-Pui National Park, northern Thailand. The experiments were designed to provide a quantitative assessment of the degree to which various tree species meet certain framework species criteria and helped to establish appropriate standards for the selection of tree species for forest restoration.

1.1. Study site

Experimental plots were established in the north of Doi Suthep-Pui National Park. After discussion with the national park authorities and villagers of Ban Mae Sa Mai (an Hmong hill tribe community in the north of the park), trial plots were positioned along or immediately below the ridges of a degraded watershed area, 2–3 km from the village (18°52′N, 98°51′E), at 1207–1310 m a.s.l. The villagers collaborated closely in all aspects of the experiments, including growing saplings in their own community nursery, as well as planting, maintaining and monitoring plots.

Originally, the study site had been covered with EGF, cleared approximately 20 years previously, to provide land for cultivation of cabbages, corn, potatoes and other cash crops. The abandoned fields were dominated by herbaceous weeds such as *Pteridium aquilinum* (L.) Kuhn (Dennstaedtiaceae), *Bidens pilosa* L. var. *minor* (Bl.) Sherf, *Ageratum conyzoides* L., *Eupatorium odoratum* L. and *E. adenophorum* Spreng. (all Compositae), *Commelina diffusa* Burm. F. (Commelinaceae) and grasses, e.g. *Phragmites vallatoria* (Pluk. ex L.) Veldk., *Imperata cylindrica* (L.) P. Beauv. var. *major* (Nees) C.E. Hubb. ex Hubb. and Vaugh. and *Thysanolaena latifolia* (Roxb. ex Horn.) Honda (both Gramineae). Most of the slopes below the plots were still cultivated (corn, cabbages, carrots, etc.), with extensive litchi orchards beyond, providing the villagers with their main source of income.

A few remnant forest trees, sparsely scattered across the plots, provided a potential seed source for natural forest regeneration. The nearest extensive patch of forest lay some 2–3 km from the plots. Fruit bats and birds, especially bulbuls were the most likely vectors of small to medium-sized seeds from forest into the plots, although remnant populations of larger vertebrates (e.g. Common Barking Deer, Common Wild Pig, Hog Badger and civets) may play a role in long-distance seed dispersal. Dispersers of the largest seeds (e.g. Asian Elephant, wild cattle, rhinos) have been extirpated from the national park. Natural recruitment of wind-dispersed trees (e.g. *Schima wallichiana* (pers. obs.)) in the plots suggests that wind is also capable of dispersing seeds of indigenous trees species over considerable distances.

Compared with soil in undisturbed EGF at a similar elevation, soil in the study site before planting was significantly more acidic and contained significantly less organic matter and nitrogen, more sand and less silt and clay, which may be a result of forest degradation (Table 1, $P < 0.05$) (Elliott et al., 2000).

The area has two main seasons: the wet season (May–October) and the dry season (mean monthly rainfall below 100 mm, November–April). The dry season is subdivided into the cool-dry season (November–January) and the hot-dry season (February–April). Average annual rainfall, recorded at the nearest weather station to the study site at similar elevation (Kog-Ma Watershed Research Station), was 2094.9 mm. Extreme temperatures ranged from a minimum of 4.5 °C in December to a maximum of 35.5 °C in March (Fig. 1).

Fire is a major constraint to reforestation in this landscape. Villagers use fire to clear land for cultivation and, despite rules to prevent accidents, fires often "escape" and burn out of control over extensive areas. Frequent anthropogenic fires are a recent occurrence

Table 1
Soil characteristics of the study site (degraded area) ($n = 16$) compared with those in undisturbed EGF (Tum Reusi, elevation 1100 m about 9 km from the study site) ($n = 20$)

	Degraded area		EGF		P-values (t-test[a])
	Mean	S.D.	Mean	S.D.	
pH	5.44	0.423	6.22	0.545	0.001
Organic matter (%)	5.35	0.997	7.30	2.480	0.010
Nitrogen (%)	0.26	0.045	0.37	0.121	0.002
Potassium (ppm)	274.84	137.637	295.67	72.093	ns[b]
Moisture at field capacity (%)	34.76	2.571	35.35	4.363	ns[b]
Sand (%)	68.52	6.290	52.13	17.872	0.010
Silt (%)	18.26	3.090	22.04	5.473	0.020
Clay (%)	13.22	3.880	25.83	16.343	0.010

[a] Two-tailed Student's t-test, variances assumed equal.
[b] Non-significant at $P > 0.05$ (Elliott et al., 2000).

in the evolutionary history of upland EGF and most species have low resistance or resilience. Fire breaks, fire look-outs and fire suppression were therefore necessary for the experiments described in this paper. However, even with such measures, fire did penetrate parts of the plots in early 2001, enabling data on the resilience of some of the planted tree species to fire to be collected.

2. Materials and methods

Thirty-seven potential framework species were selected (Table 2) on the basis of FORRU's previous research (Blakesley et al., 2002; Elliott et al., 2002).

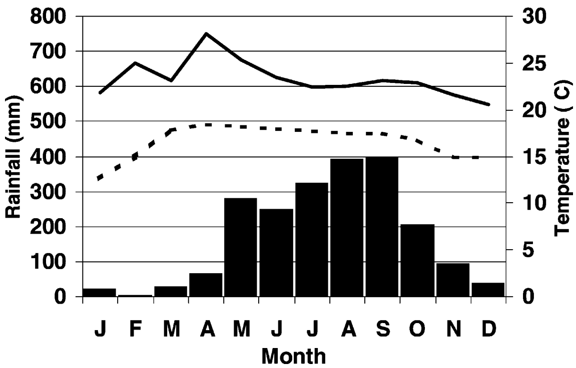

Fig. 1. Average monthly rainfall (solid bars), maximum and minimum temperatures (solid and broken lines, respectively) at Kog-Ma Watershed Research Station (elevation 1400 m) approximately 9 km from the study site (1966–1983).

Seed of each species were collected within Doi Suthep-Pui National Park at the time of fruit ripening and immediately sown in plastic trays in a medium of forest soil and coconut husk mixed in the ratio 1:1. Seedlings were pricked out when the first pair of leaves had fully expanded and transplanted into black plastic bags (6.5 cm × 23 cm) in a medium of forest soil, peanut husk and coconut husk (2:1:1). Seedlings were shaded inside the nursery under a plastic roof (approximately 20% full sunlight) for 2 weeks and a nitrogenous fertiliser (45–0–0) was applied every 2 days. Seedlings were placed outside, under black shade netting (slan, approximately 50% of full sunlight) for 3–18 months, depending on the species. Ten granules of Osmocote slow-release fertiliser (15–15–15) were applied every three months and weeds, pests and diseases controlled as required for each species. Saplings ready for planting out (50–60 cm tall) were hardened off in full sunlight and dispatched for planting in June each year. Only healthy, good quality saplings were planted out.

About 1 month before planting, the plots were demarcated with large wooden poles and the weeds slashed with hand tools to reveal any naturally established trees or saplings. About a week after cutting the weeds, the area was sprayed with a single application of the non-residual herbicide, glyphosate, to kill weed roots and prevent immediate regrowth. During all weeding operations, care was taken to avoid cutting or spraying natural trees or saplings.

Saplings were planted randomly at a density of 3125 ha^{-1}, averaging a mean distance between plants

Table 2
Mean percent survival at the end of the second growing season (17 months after planting) of tree species planted in 1998 and 1999

Tree species	Family	1998 planting			1999 planting		
		n[a]	Mean percentage of survival[b]	S.D.	n[a]	Mean percentage of survival[b]	S.D.
Acrocarpus fraxinifolius Wight ex Arn.	Caesalpinioideae				48	25.0	10.9
Aglaia lawii (Wight) Sald. and Rama.	Meliaceae	71	54.7	15.9			
Bischofia javanica Bl.	Euphorbiaceae	84	92.6	3.7			
Balakata baccata (Roxb.) Ess.	Euphorbiaceae				48	45.8	13.0
Callicarpa arborea Roxb. var. *arborea*	Verbenaceae				48	31.2	12.5
Castanopsis acuminatissima (Bl.) A. DC.	Fagaceae				48	62.5	16.6
Cinnamomum caudatum Nees	Lauraceae				48	37.5	6.3
Diospyros glandulosa Lace	Ebenaceae	108	37.0	3.2			
Erythrina subumbrans (Hassk.) Merr.	Papilionoideae	48	89.5	7.2	48	58.3	25.3
Ficus altissima Bl.	Moraceae	48	85.4	9.5			
Ficus benjamina L. var. *benjamina*	Moraceae				48	70.8	9.6
Ficus glaberrima Bl. var. *glaberrima*	Moraceae				48	85.4	9.5
Ficus heteropleura Bl. var. *heteropleura*	Moraceae				48	54.1	9.6
Ficus hispida L. f. var. *hispida*	Moraceae				48	87.5	16.6
Ficus racemosa L. var. *racemosa*	Moraceae				48	70.8	7.2
Ficus subulata Bl. var. *subulata*	Moraceae				48	72.3	66.8
Glochidion kerrii Craib	Euphorbiaceae				48	47.9	3.6
Gmelina arborea Roxb.	Verbenaceae	48	75.0	6.3	48	60.4	7.2
Helicia nilagirica Bedd.	Proteaceae	96	70.8	13.0			
Heynea trijuga Roxb. ex Sims	Meliaceae				48	72.9	7.2
Horsfieldia thorelii Lec.	Myristicaceae				48	20.8	21.9
Hovenia dulcis Thunb.	Rhamnaceae	60	80.0	8.7	48	85.4	9.5
Lithocarpus fenestratus (Roxb.) Rehd.	Fagaceae				48	33.3	7.2
Macaranga denticulata (Bl.) M.-A.	Euphorbiaceae				48	29.1	23.6
Machilus bombycina King ex Hk.f.	Lauraceae				48	66.6	9.6
Manglietia garrettii Craib	Magnoliaceae	108	48.2	16.3			
Melia toosendan Sieb. and Zucc.	Meliaceae	60	98.3	2.9	48	60.4	13.0
Michelia baillonii Pierre	Magnoliaceae				47	61.5	11.8
Nyssa javanica (Bl.) Wang.	Nyssaceae				48	56.2	16.5
Phoebe cathia (D. Don) Kosterm.	Lauraceae				48	18.7	6.3
Prunus cerasoides D. Don	Rosaceae	60	86.7	2.9	48	47.9	9.5
Pterocarpus macrocarpus Kurz	Papilionoideae				48	45.6	15.5
Quercus semiserrata Roxb.	Fagaceae	60	71.7	14.4	48	47.9	14.4
Rhus rhetsoides Craib	Anacardiaceae				48	87.2	5.9
Sapindus rarak DC.	Sapindaceae	84	79.5	7.8	48	25.0	6.3
Sarcosperma arboreum Bth.	Sapotaceae	84	76.2	10.3			
Spondias axillaris Roxb.	Anacardiaceae	89	93.5	6.3			

[a] Total number of trees planted.
[b] Averaged across three replicated plots of 1600 m^2.

of 1.8 m, with 29 or 30 species planted in each plot. The planting mixture varied from year to year, due to availability of saplings, but the same species mix was used in all three replicates planted each year.

The data presented in this paper come from six 0.16 ha plots, three planted in mid-June in 1998, and three in mid-June 1999. June was selected, as the optimal planting month, because the rains have usually become regular by this time, and planted saplings would have the maximum time for growth and development (especially the root system) before the onset of the dry season. At least 48 saplings of each species were transported to the upper watershed planting area, and planted in a single day. One hundred grams of fertiliser (NPK 15–15–15, Rabbit Brand) was mixed in with loose soil at the bottom of each planting hole immediately prior to planting. Subsequently, weeding with hand tools was carried out three times during the rainy season at 4–6 week intervals. Immediately after weeding, further 100 g doses of fertiliser were applied in a ring around each tree (at least 30 cm away from the stem).

All trees were monitored for survival 2 weeks after planting, and at the end of the wet season, cool season and dry season in the first year, and annually at the end of the wet season thereafter. Sub-samples of saplings (15–30 individuals depending on availability) were randomly selected for more intensive monitoring of height (distance from ground level to the highest meristem); root collar diameter, crown width (at widest point) and weed cover (measured on a three-point scale, from 0 = bare earth to 3 = 100% weed cover in a circle of radius 50 cm around the stem of the planted tree).

The provision of resources for wildlife was assessed by direct observation of flowering and fruiting of the planted trees. In March 2001, a moderate litter fire spread through parts of one of the 1998 plots and one 1999 plot. This enabled an assessment to be made of the ability of most of the species planted to recover after fire. All trees that had been burnt were monitored 2 weeks after the fire and again after 5 months, by measuring the height and root collar diameter of planted trees.

To assess the extent to which the various species planted met the framework species criteria, minimum acceptable standards were proposed. Trees were planted in June, at the beginning of the wet season and grew rapidly until the rains ceased in November. In the first dry season after planting (November–April), growth slowed and those trees which failed to survive were assumed to have succumbed to drought stress resulting from a failure to develop an adequate root system. By the end of the second wet season (i.e. after 17 months), planted trees had either established well or had died. This was therefore considered to be the optimal time to assess tree performance.

The acceptable survival rate for any species was considered 50% or more by the end of the second growing season, excellent survival being considered as 70% or more. Species with survival rates of 45–49.9% were considered to be marginally acceptable. We considered that a mean height of 1.5 m or more by the end of the second growing season was acceptable, as this amounts to a more than doubling of seedling height within 17 months. A mean height of 2 m or more by the end of the second growing season was classed as exceptional growth, whilst 1.25–1.49 m was considered marginally acceptable.

Canopy closure is an important milestone in forest restoration, creating cooler, shadier and moister conditions on the forest floor and the accumulation of leaf litter that should suppress weeds and encourage establishment of forest tree seedlings. Since trees were planted 1.8 m apart, a crown width of 1.8 m or more, by the end of the second growing season, should enable a tree to close canopy with its nearest neighbours. We therefore considered a mean crown width of 1.8 m by the end of the second growing season after planting as excellent, 1.5–1.8 m as acceptable, 1.0–1.5 m as marginal and less than 1.0 m as unacceptable.

We found no clear correlation between canopy width and reduction in weed cover score in a 1 m diameter circle around the base of the planted trees. Therefore, the reduction in weed cover score between the end of the first growing season after planting and the end of the second growing season after planting was used to compare species' abilities to suppress growth of herbaceous weeds. A reduction in mean weed score of 1.0 or more was considered excellent, 0.5–1.0 acceptable, 0.40–0.49 marginal and less than 0.40 unacceptable.

Standards of survival after the single fire event of early 2000 followed those for overall survival: 70% survival or higher was considered to indicate excellent fire resilience; 50–69.9% acceptable; 45–49.9% marginal and less than 45% unacceptable.

3. Results

3.1. Survival

Table 2 shows the mean percent survival of 37 candidate framework tree species at the end of the second growing season after planting, tested in the six plots planted in 1998 and 1999. Of the 15 species, assessed in the 1998 plots, 12 maintained excellent survival rates of 70% or higher until the end of the second growing season (*Bischofia javanica*, *Erythrina subumbrans*, *Ficus altissima*, *Gmelina arborea*, *Helicia* *nilagirica*, *Hovenia dulcis*, *Melia toosendan*, *Prunus cerasoides*, *Quercus semiserrata*, *Sapindus rarak*, *Sarcosperma arboreum* and *Spondias axillaris*). One further species, *Aglaia lawii* var. *wallichiana* had an 'acceptable' survival rate of 55%. With a survival rate of 48%, *Manglietia garrettii* was ranked as marginally acceptable, whilst *Diospyros glandulosa* substantially failed to attain the proposed minimum standard survival rate.

For six of the seven species planted in both 1998 and 1999, survival was lower amongst trees planted in 1999 than amongst those planted in 1998. This may have been due to a 5-day period with no rain, immediately after planting. Widespread drying out and browning of leaves was noted for many species within 1–2 weeks after planting, especially on ridge-top sites exposed to the wind. Since the plots are above any springs and difficulty of access makes transportation of water impractical, rainfall shortly after planting greatly increases the likelihood that transplanted saplings will successfully establish. Such rainfall can normally be relied upon in June, but in 1999 it did not occur.

Eight of the 29 species assessed in 1999 maintained excellent survival rates of 70% or higher through to the end of the second growing season (*Ficus benjamina* var. *benjamina*, *Ficus glaberrima* var. *glaberrima*, *Ficus hispida* var. *hispida*, *Ficus racemosa* var. *racemosa*, *Ficus subulata* var. *subulata*, *H. trijuga*, *H. dulcis* and *Rhus rhetsoides*). These species appear to tolerate short periods without rain immediately after planting. In addition, a further eight species maintained acceptable survival rates of 50–69% (*Castanopsis acuminatissima*, *E. subumbrans*, *Ficus heteropleura* var. *heteropleura*, *G. arborea*, *Machilus bombycina*, *M. toosendan*, *Michelia baillonii*, and *Nyssa javanica*). Five other species had survival rates only marginally lower than 50% (*Balakata baccata*, *Glochidion kerrii*, *P. cerasoides*, *Pterocarpus macrocarpus* and *Q. semiserrata*). Eight species had survival rates lower than 45%. Included in these was *S. rarak*, which attained a high survival rate in the 1998 experiment, but which presumably suffered high post-planting mortality, due to a short period without rain, in the 1999 experiment. This species should therefore not be rejected as framework species due to low survival in the 1999 experiment. The following eight species had unacceptably low survival rates in the 1999 trials: *Acrocarpus fraxinifolius*, *Callicarpa arborea*, *Cinnamomum caudatum*, *D. glandulosa*, *Horsfieldia thorelii*, *Lithocarpus fenestratus*, *Macaranga denticulata* and *Phoebe cathia*.

3.2. Growth

The number of transplanted saplings of each species, measured at the end of the second growing season after planting ranged from 8 to 19, since mortality amongst the randomly selected saplings varied (Table 3). Eleven species displayed excellent growth, attaining mean heights of 2 m or taller by the end of the second growing season: *A. fraxinifolius*, *B. baccata*, *E. subumbrans*, *H. dulcis*, *M. denticulata*, *M. toosendan*, *Michelia bailonii*, *N. javanica*, *P. cerasoides*, *R. rhetsoides* and *S. axillaris*. An additional three species achieved acceptable growth: *F. hispida*, *G. arborea* and *M. bombycina*, whilst a further five were considered marginal: *C. acuminatissima*, *D. glandulosa*, *F. racemosa* var. *racemosa* and *M. garrettii* and *S. rarak*. The remaining 18 species (nearly half of those tested) substantially failed to meet the proposed minimum growth standard (Table 3).

3.3. Crown width and weed suppression

A mean crown width of 1.8 m or more by the end of the second growing season proved to be a very stringent standard, with only seven of the 37 species tested attaining it in either or both the 1998 and 1999 plantings: *Acrocaprus fraxinifolius*, *B. baccata*, *E. subumbrans*, *M. denticulata*, *M. toosendan*, *P. cerasoides* and *S. axillaris* (Table 3). A further 14 species reached acceptable or marginally acceptable mean crown widths of 1 m or more: *C. acuminatissima*, *C. caudatum*, *F. glaberrima* var. *glaberrima*, *F. hispida* var. *hispida*, *F. racemosa* var. *racemosa*, *F. subulata* var. *subulata*, *G. arborea*, *H. dulcis*, *M. bombycina*, *M. garrettii*, *M. baillonii*, *N. javanica*, *R. rhetsoides* and *S. arboreum*. The remaining 16 species developed unacceptably narrow crowns that would require considerable further growth to close canopy with their neighbours.

Although a broad crown is a desirable characteristic of framework species, enabling rapid canopy closure, no clear correlation between crown width and weed cover reduction was detected at this early stage. However, the majority of tree species tested (25)

Table 3
Mean tree height and mean crown width at the end of the second growing season (17 months after planting) of tree species planted in 1998 and 1999[a]

Tree species	1998 planting			1999 planting		
	n[b]	Mean height (cm)	Mean crown width (cm)	n[b]	Mean height (cm)	Mean crown width (cm)
A. fraxinifolius Wight ex Arn.				7	210.0 (107.1)	192.6 (124.0)
A. lawii (Wight) Sald. and Rama.	8	36.9 (13.3)	34.7 (9.4)			
B. javanica Bl.	10	86.9 (23.3)	87.9 (12.0)			
B. baccata (Roxb.) Ess.				11	309.4 (67.6)	253.9 (253.9)
C. arborea Roxb. var. *arborea*				7	118.9 (71.7)	94.4 (69.9)
C. acuminatissima (Bl.) A. DC.				14	135.2 (41.3)	112.1 (42.6)
C. caudatum Nees				9	102.1 (32.4)	111.1 (38.0)
D. glandulosa Lace	12	126.4 (117.7)	85.3 (37.1)			
E. subumbrans (Hassk.) Merr.	11	258.7 (72.9)	261.5 (92.6)	10	281.5 (51.0)	280.2 (82.5)
F. altissima Bl.	9	117.1 (95.8)	91.5 (36.7)			
F. benjamina L. var. *benjamina*				11	77.7 (44.9)	81.0 (38.1)
F. glaberrima Bl. var. *glaberrima*				12	117.1 (45.9)	110.5 (41.2)
F. heteropleura Bl. var. *heteropleura*				10	77.4 (51.1)	65.1 (40.4)
F. hispida L. f. var. *hispida*				11	159.6 (85.5)	126.9 (72.1)
F. racemosa L. var. *racemosa*				10	140.8 (47.9)	115.9 (46.6)
F. subulata Bl. var. *subulata*				7	105.6 (131.7)	105.6 (131.7)
G. kerrii Craib				9	75.0 (29.5)	61.2 (20.5)
G. arborea Roxb.	10	160.8 (66.9)	146.3 (51.7)	9	180.1 (53.4)	159.9 (95.7)
H. nilagirica Bedd.	16	74.1 (58.4)	57.5 (23.3)			
H. trijuga Roxb. ex Sims				12	100.9 (41.7)	62.6 (29.3)
H. thorelii Lec.				6	48.3 (17.2)	36.8 (13.2)
H. dulcis Thunb.	10	155.1 (51.5)	133.9 (61.8)	13	223.1 44.4)	148.5 (35.4)
L. fenestratus (Roxb.) Rehd.				8	109.9 (30.4)	70.9 (30.7)
M. denticulata (Bl.) M.-A.				9	259.0 (106.5)	200.9 (85.6)
M. bombycina King ex Hk.f.				14	182.0 (40.6)	111.6 (29.5)
M. garrettii Craib	11	145.5 (73.9)	124.4 (25.1)			
M. toosendan Sieb. and Zucc.	13	535.1 (133.4)	255.2 (179.6)	12	705.8 (309.5)	235.2 (70.3)
M. baillonii Pierre				15	205.5 (71.5)	156.2 (42.6)
N. javanica (Bl.) Wang.				12	219.8 (37.2)	165.8 (69.0)
P. cathia (D. Don) Kosterm.				8	79.6 (19.0)	77.1 (32.5)
P. cerasoides D. Don	10	241.0 (88.1)	188.7 (55.2)	6	303.3 (37.2)	241.7 (102.1)
P. macrocarpus Kurz				7	43.4 (21.9)	21.0 (9.9)
Q. semiserrata Roxb.	10	104.5 (53.3)	68.2 (30.6)	9	114.9 (24.9)	66.0 (22.5)
R. rhetsoides Craib				12	306.7 (94.3)	135.7 (46.5)
S. rarak DC.	15	107.9 (63.0)	77.7 (24.7)	10	126.5 (45.6)	92.3 (40.4)
S. arboreum Bth.	15	100.6 (67.6)	100.7 (26.9)			
S. axillaris Roxb.	19	255.7 (100.6)	213.5 (76.6)			

[a] Values in brackets represent S.D.
[b] Subsamples of surviving trees.

reduced weed cover score by 1.0 or greater between the end of the first and end of the second growing seasons (Table 4) and were classed as 'excellent' weed suppressers (Table 6). An additional 10 species brought about an 'acceptable' or 'marginally acceptable' reduction in weed cover (Table 6). Only two species (*A. lawii* and *D. glandulosa*) failed to have a substantial effect on weeds. It is interesting to note that the species ranked as 'excellent' weed suppressers included all those species with 'excellent' crown width, as well as many with merely 'acceptable, marginal or unacceptable' crown width. This suggests that even relatively narrow crowned trees are still able to have an effect on surround herbaceous weeds.

Table 4
Reduction in weed cover at the end of the second growing season (17 months after planting) associated with tree species planted in 1998 and 1999

Tree species	1998 planting			1999 planting		
	n[a]	Mean reduction in weed score[b]	S.D.	n[a]	Mean reduction in weed score[b]	S.D.
A. fraxinifolius Wight ex Arn.				7	1.79	0.81
A. lawii (Wight) Sald. and Rama.	8	0.37	0.58			
B. javanica Bl.	10	0.40	0.21			
B. baccata (Roxb.) Ess.				7	2.14	1.07
C. arborea Roxb. var. *arborea*				4	0.87	0.63
C. acuminatissima (Bl.) A. DC.				9	1.44	1.01
C. caudatum Nees				2	1.0	1.41
D. glandulosa Lace	8	0.37	0.35			
E. subumbrans (Hassk.) Merr.	10	0.60	0.32	8	1.19	0.96
F. altissima Bl.	7	0.50	0.50			
F. benjamina L. var. *benjamina*				9	0.89	1.45
F. glaberrima Bl. var. *glaberrima*				9	1.61	0.93
F. heteropleura Bl. var. *heteropleura*				7	1.29	0.76
F. hispida L. f. var. *hispida*				9	1.61	1.02
F. racemosa L. var. *racemosa*				7	1.43	0.97
F. subulata Bl. var. *subulata*				6	1.75	0.88
G. kerrii Craib				5	1.20	1.30
G. arborea Roxb.	9	0.56	0.46	8	1.44	0.94
H. nilagirica Bedd.	15	0.40	0.43			
H. trijuga Roxb. ex Sims				8	1.75	0.93
H. thorelii Lec.				2	2.25	0.35
H. dulcis Thunb.	9	0.61	0.33	11	1.36	0.68
L. fenestratus (Roxb.) Rehd.				6	1.08	1.11
M. denticulata (Bl.) M.-A.				2	2.5	0.7
M. bombycina King ex Hk.f.				9	0.94	0.68
M. garrettii Craib	11	0.64	0.23			
M. toosendan Sieb. and Zucc.	10	0.35	0.34	9	1.78	0.67
M. baillonii Pierre				10	1.25	1.03
N. javanica (Bl.) Wang.				6	0.67	0.82
P. cathia (D. Don) Kosterm.				6	1.42	1.69
P. cerasoides D. Don	10	0.45	0.16	3	1.67	2.31
P. macrocarpus Kurz				4	2.25	0.5
Q. semiserrata Roxb.	7	0.5	0.29	9	1.11	1.05
R. rhetsoides Craib				12	1.37	0.97
S. rarak DC.	15	0.47	0.52	4	1.75	0.5
S. arboreum Bth.	15	0.50	0.42			
S. axillaris Roxb.	16	0.59	0.52			

[a] Subsamples of surviving trees.
[b] Between end of the first and end of the second growing season.

3.4. Potential attractiveness to wildlife

Since most tree species take more than 2 years to mature and produce flowers or fruits likely to attract wildlife, it was not possible to assess the attractiveness of all planted species to wildlife within the time frame of this project. However, five species did produce flowers and fruits likely to be attractive to animals within 2.5 years. Most *P. cerasoides* trees flowered and fruited (red, fleshy drupes) 2.5 years after planting; all *F. subulata* individuals produced figs almost continuously from the time of planting onwards;

several *E. subumbrans* trees produced nectar-rich flowers 2.5 years after planting and one specimen of *Q. semiserrata* produced acorns 1.5 years after planting. *M. toosendan* commonly flowered and fruited 3.5 years after planting. In addition, *C. acuminatissima* was used as a nesting tree by birds 2.5 years after planting.

3.5. Resilience after burning

Table 5 shows the resilience of the candidate framework species following a moderate litter fire in March 2001. Trees planted in 1998 were 33 months old (three growing seasons) at the time of the fire, whilst those planted in 1999 were 21 months old

Table 5
Resilience to fire exhibited by a subsample of trees planted in 1998 and 1999

Tree species	Planting year	Number of trees burnt	Percentage of burnt trees surviving	Root collar diameter (mm)	
				Largest tree that died	Smallest tree that survived
A. fraxinifolius Wight ex Arn.	1999	10	70	77	20
A. lawii (Wight) Sald. and Rama.		0			
B. javanica Bl.	1998	8	87	62	20
B. baccata (Roxb.) Ess.	1999	19	26	84	57
C. arborea Roxb. var. *arborea*		0			
C. acuminatissima (Bl.) A. DC.	1999	32	66	43	13
C. caudatum Nees	1999	20	60	53	5
D. glandulosa Lace		0			
E. subumbrans (Hassk.) Merr.	1999	18	22	120	75
F. altissima Bl.	1998	14	86	56	38
F. benjamina L. var. *benjamina*	1999	22	45	70	10
F. glaberrima Bl. var. *glaberrima*	1999	32	50	48	17
F. heteropleura Bl. var. *heteropleura*	1999	7	43	17	9
F. hispida L. f. var. *hispida*	1999	22	77	80	7
F. racemosa L. var. *racemosa*	1999	18	83	51	21
F. subulata Bl. var. *subulata*		0			
G. kerrii Craib	1999	10	70	15	9
G. arborea Roxb.	1999	24	83	90	15
H. nilagirica Bedd.		0			
H. trijuga Roxb. ex Sims	1999	15	67	58	2
H. thorelii Lec.	1999	8	25	14	18
H. dulcis Thunb.	1999	29	76	42	8
L. fenestratus (Roxb.) Rehd.	1999	9	67	18	11
M. denticulata (Bl.) M.-A.	1999	15	53	69	30
M. bombycina King ex Hk.f.	1999	27	85	29	13
M. garrettii Craib		0			
M. toosendan Sieb. and Zucc.	1998	6	100	–	42
	1999	20	70	110	55
M. baillonii Pierre	1999	21	71	49	16
N. javanica (Bl.) Wang.	1999	27	41	170	27
P. cathia (D. Don) Kosterm.	1999	10	50	33	10
P. cerasoides D. Don	1999	20	60	39	12
P. macrocarpus Kurz	1999	7	29	25	9
Q. semiserrata Roxb.	1998	6	33	23.5	15
	1999	24	33	22	6
R. rhetsoides Craib	1999	27	93	80	87
S. rarak DC.	1998	7	100	–	10
	1999	16	56	40	18
S. arboreum Bth.	1998	7	86	22	17
S. axillaris Roxb.	1998	13	100	–	35

(two growing seasons). All tree species planted in 1998 that burnt had exceptionally high survival rates (80–100%), except *Q. semiserrata*. This result clearly demonstrates that by three growing seasons after planting, most candidate framework tree species have reached a sufficiently large size to recover well after a moderate litter burn.

The trees planted in 1999, however, were smaller and showed greater variability in their responses to fire. Fifteen species showed exceptional resilience to fire, maintaining survival rates after burning of 70% or higher (Table 6). Eleven others had acceptable or marginally acceptable survival rates after burning (Table 6). Only five species were seriously depleted

Table 6
Summary of framework species classification based on field performance (E, excellent; A, acceptable; M, marginal; U, unacceptable and R, rejected)

Tree species	Survival[a]	Growth[b]	Crown width[c]	Weed suppression[d]	Fire resilience[a]	Overall classification
A. fraxinifolius Wight ex Arn.	U	E	E	E	E	A
A. lawii (Wight) Sald. and Rama.	A	U	U	U	–	R
B. javanica Bl.	E	U	U	M	E	M
B. baccata (Roxb.) Ess.	M	E	E	E	U	A
C. arborea Roxb. var. *arborea*	U	U	U	A	–	R
C. acuminatissima (Bl.) A. DC.	A	M	M	E	A	A
C. caudatum Nees	U	U	M	E	A	R
D. glandulosa Lace	U	M	U	U	–	R
E. subumbrans (Hassk.) Merr.	E	E	E	E	U	E
F. altissima Bl.	E	U	U	A	E	A
F. benjamina L. var. *benjamina*	E	U	U	A	M	A
F. glaberrima Bl. var. *glaberrima*	E	U	M	E	A	A
F. heteropleura Bl. var. *heteropleura*	A	U	U	E	M	M
F. hispida L. f. var. *hispida*	E	A	M	E	E	E
F. racemosa L. var. *racemosa*	E	M	M	E	E	A
F. subulata Bl. var. *subulata*	E	U	M	E	–	A
G. kerrii Craib	M	U	U	E	E	A
G. arborea Roxb.	E	A	A	E	E	E
H. nilagirica Bedd.	E	U	U	M	–	R
H. trijuga Roxb. ex Sims	E	U	U	E	A	A
H. thorelii Lec.	U	U	U	E	U	R
H. dulcis Thunb.	E	E	M	E	E	E
L. fenestratus (Roxb.) Rehd.	U	U	U	E	A	R
M. denticulata (Bl.) M.-A.	U	E	E	E	A	A
M. bombycina King ex Hk.f.	A	A	M	A	E	A
M. garrettii Craib	M	M	M	A	–	M
M. toosendan Sieb. and Zucc.	E	E	E	E	E	E
M. baillonii Pierre	A	E	A	E	E	E
N. javanica (Bl.) Wang.	A	E	A	A	M	A
P. cathia (D. Don) Kosterm.	U	U	U	E	A	R
P. cerasoides D. Don	E	E	E	E	A	E
P. macrocarpus Kurz	M	U	U	E	U	R
Q. semiserrata Roxb.	E	U	U	E	U	M
R. rhetsoides Craib	E	E	M	E	E	E
S. rarak DC.	E	M	U	E	E	A
S. arboreum Bth.	E	U	M	A	E	A
S. axillaris Roxb.	E	E	E	A	E	E

[a] E > 70%, A = 50–69.9%, M = 45–49.9%, U < 45%.
[b] E > 2.0 m, A = 1.5–1.99 m, M = 1.25–1.49 m, U < 1.25 m.
[c] E > 1.8 m, A = 1.5–1.79 m, M = 1.0–1.5, U =< 1.0 m.
[d] E > 1, A = 0.5–1.0, M = 0.4–0.49, U < 0.40.

as a result of the fire, with post-burn survival rates substantially less than 50%. These species (*B. baccata*, *E. subumbrans*, *H. thorelii*, *P. macrocarpus*, *Q. semiserrata*) should probably not be used as framework tree species in attempts to restore forest ecosystems on particularly fire-prone sites where effective fire prevention measures cannot be guaranteed.

4. Discussion

This study quantified, for the first time, the field performance of 37 candidate framework species, in the harsh environmental conditions of a degraded upper watershed in northern Thailand. Whilst there have been numerous studies of tree regeneration in natural gaps in tropical forests (Hartshorn, 1978; Popma et al., 1988; Osunkoya et al., 1993), less attention has been focused on degraded forestland, which has been farmed. To our knowledge no reports on the performance of framework species in any tropical forest types have been published.

We defined criteria and proposed minimum acceptable standards, by which framework species can be identified. Low percentage survival is the most important reason to reject a tree species as a framework species, since it necessitates expensive re-planting. A high growth rate is also important to elevate the tree crown above the weeds and a broad dense crown to shade out weeds. However, a few slow-growing species might be tolerated, to diversify canopy structure and create a greater diversity of understorey niches for wildlife. Similarly, a few species with narrow crowns might be acceptable in the planting mixture, provided they perform well in most other respects. Resilience after burning is also a significant criterion in northern Thailand, where wildfires are widespread and frequent during the hot-dry season (February–April). However, resilience to fire is not an essential criterion where fires are rare or where fire prevention measures are efficient.

Table 6 provides a summary of the extent to which each species met or exceeded the minimum proposed standards. The candidate framework species were divided into four categories. Those considered to be 'excellent' had high survival rates and exceeded most of the other framework standards. 'Acceptable' species were those, which exhibited good but not outstanding performance in all, or most of the criteria considered. 'Marginal' species exceeded some but not all the framework standards. The latter may be useful as framework tree species for forest restoration with more intensive silvicultural treatments after planting, or through the production of better quality planting stock, or if planted in combination with 'excellent' or 'acceptable' species. Finally, species were 'rejected' as framework species if they substantially failed to meet all or most of the framework standards.

Nine species were ranked as excellent framework species. Despite low fire resistance *E. subumbrans* was ranked as excellent, since it greatly exceeded all other standards and would have very high performance on fire free sites. Parrotta and Knowles (2001), studying the restoration of lowland moist tropical forest in Brazil, classified 37% of 160 species systematically evaluated for a 'high-diversity' planting scheme as 'well adapted'. Criteria used were similar to those applied in this study, namely survival (>75%) and vigorous shoot growth, assessed during the first 2 years.

Seventeen species were ranked as 'acceptable' framework species. *A. fraxinifolius* and *M. denticulata* were included, despite having 'unacceptable' survival. The low survival rate of these species was only recorded following the rainless period after planting in 1999. It was considered that these species would most likely have much higher survival in years of more normal rainfall patterns and they scored very highly for all other criteria. Parrotta and Knowles (2001) identified an additional 19% of their species as 'fair', with good shoot growth and survival rates of 50–75%, similar to the standard applied in this study. Five other species in our study had 'unacceptable' narrow crowns, but in every case this was counterbalanced by 'acceptable' or 'excellent' weed suppression, so narrow crowns were not seen as a disadvantage, especially since they would add structural diversity to a framework forest.

In addition to high field performance, all species in the 'excellent', 'acceptable' or 'marginal' categories were easily propagated in the nursery (Blakesley et al., 2002; unpublished data) except *M. bombycina*, which has low rates of seed germination and low seedling survival in the nursery. Further work on the effective propagation of this species is required before it can be widely recommended. Only nine species performed poorly in most respects and should probably be rejected as framework species.

Several species planted in both 1998 and 1999 had substantial differences in survival and growth rates between the two planting years. Generally lower survival in 1999 was attributable to a rainless period of 5 days immediately after planting, when adequate water supply to the roots is essential to prevent transplantation shock. However, for trees planted in 1999 that survived, growth was generally higher than for trees planted in 1998. This might be explained by better conditions for growth in the 2000 growing season or by a reduction in competition due to reduced tree density, resulting from the high mortality rates during the 1999 growing season.

It is too early to assess the ability of framework tree species to attract wildlife into planted plots. Attractiveness to wildlife is a property that develops over time and can only be assessed as the trees mature. Tucker and Murphy (1997) reported the recruitment of up to 72 plant species in 7-year old plots, though recruitment into 5-year old plots was less abundant and diverse. The ability of attracted wildlife to deposit seeds, which then germinate and enhance forest plant diversity in our plots, requires more detailed research. Long-term monitoring of the establishment of new species in the plots, across many life forms is therefore needed to assess the final outcome of forest restoration plantings.

The experiments described in this paper were located on formerly cultivated, evergreen forestland in the seasonally dry climate of northern Thailand, at elevations of approximately 1200–1300 m. A pertinent question is: how effectively could the framework tree species, identified by this research, be used to restore forest ecosystems elsewhere? Since the primary objective of the framework species methods is restoration of natural forests for conservation of biodiversity, the framework species identified by this paper should only be planted within their natural elevational and geographical ranges. For most species, these are detailed in FORRU (2000). Maxwell and Elliott (2001) show that the floristic composition of evergreen forest on mountains in northern Thailand is very similar, from approximately 1000 m elevation up to the summit of Thailand's highest mountain (Doi Inthanon, 2565 m a.s.l.). This suggests that many of the framework species identified in this paper would probably have broad application in the restoration of evergreen forest ecosystems, provided adequate silvicultural care is applied. Furthermore, several of the tree species ranked as ''excellent'' have very wide elevational ranges and might even have potential for the restoration of deciduous forest ecosystems at low elevations. For example, *M. toosendan* and *E. subumbrans* show promising survival and growth rates, when planted on deciduous forestland at 350 m elevation (FORRU, unpublished data). However, further field trials, under a wider range of environmental conditions, would clearly be useful to determine the full range of conditions under which each species conforms to framework criteria.

Perhaps a more important question is: to what extent can the general approach described in this paper be applied to identify framework tree species suitable for restoring forests in other bio-geographical realms? We believe that the criteria for species selection for restoration of biodiversity-rich forest ecosystems initially identified by Goosem and Tucker (1995) and developed in this paper can be broadly applied to all tropical forest ecosystems. Goosem and Tucker (1995) advocated the framework species method for restoration to areas close to large tracts of intact, primary forests. However, FORRU's work is showing that the method works well, wherever there are remnant seed trees in the landscape, even if intact forest is several kilometres away, provided a basic assemblage of seed-dispersing birds and bats remains.

More debatable is the usefulness of the minimum acceptable performance standards proposed in this paper. The purpose of these standards was to enable useful comparisons to be made amongst a group of selected, candidate frameworks species. Whilst the standards are probably useful for other areas in northern Thailand, they may need to be applied with greater flexibility elsewhere. Tree species meeting framework standards on one site might fail to do so on another, due to variations in site conditions. This paper also shows variability in ability of species to meet the standards in different years, due to inter-annual variation in the climate. Therefore, framework species selection should be based on comparisons among species planted at the same time on each particular site. It was uncommon for species to exceed all framework standards. The aim should be to plant a mixture of 20–30 relatively high performing tree species that collectively re-create the essential elements of a forest ecosystem, particularly biodiversity and ecological functioning. If all tree species planted met all framework standards, the result might be a uniform canopy formed by fast growing, similarly structured trees. Therefore, some flexibility is needed in using the proposed standards, based on local conditions, management objectives and common-sense.

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