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Author for correspondence:
Pimonrat Tiansawat
e-mail: pimonrat.t@cmu.ac.th

The framework species method: harnessing natural regeneration to restore tropical forest ecosystems

Stephen Elliott[1,2], Nigel I. J. Tucker[3], Dia Panitnard Shannon[1,2] and Pimonrat Tiansawat[1,2]

[1]Forest Restoration Research Unit, Department of Biology, Faculty of Science, and [2]Environmental Science Research Centre, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand
[3]College of Science and Engineering, James Cook University, Cairns QLD3811, Australia

SE, 0000-0002-5846-3353; PT, 0000-0003-1354-1247

As interest in restoring tropical forests surges, so does the need for effective methods to ensure success. The framework species method (FSM) restores forest ecosystems by densely planting open sites, close to natural forest, with woody species, indigenous to the reference ecosystem and selected for their ability to accelerate ecological succession. Criteria for selecting framework species include: (i) representative of the reference forest ecosystem, (ii) tolerant of open conditions, (iii) ability to suppress weeds, (iv) attractiveness to seed-dispersing animals and (v) easily propagated. The method is effective where forest remnants and viable populations of seed dispersers remain. The origins and elements of the FSM are discussed. We review its adoption in 12 countries. Adherence to original principles was mostly high, but some misuse of the term was evident. The need for clearer definitions was identified. We place the FSM on a scale of restoration methods, matched with degradation levels and compare its establishment costs with those of other methods. Obstacles to its wider adoption, both technical and socio-economic, are discussed, along with how these might be overcome. Finally, the FSM is more clearly defined to facilitate its use in contributing towards the goals of the UN Decade on Restoration.

This article is part of the theme issue 'Understanding forest landscape restoration: reinforcing scientific foundations for the UN Decade on Ecosystem Restoration'.

1. Introduction

Over the past few decades, the idea that tropical forest ecosystems can be restored to original levels of biodiversity and ecological functioning has transitioned from the wishful thinking of a few conservationists, to the global necessity it has become today. Extensive tree planting is being implemented on every tropical continent, driven by the realization that forest restoration can mitigate climate change through carbon sequestration, reduce biodiversity loss and alleviate poverty [1]. However, large-scale tree-planting projects have been criticized for focusing on the quantity of trees planted, rather than on achievement of socio-ecological benefits [2]. About two-thirds of the area pledged for reforestation under the Bonn Challenge [3] are plantations and agroforests, with only one-third undergoing ecological restoration, even though the latter sequesters carbon on average 40 times more efficiently than plantations [4], and it supports far greater biodiversity recovery. Mass tree planting sometimes results in the use of tree species that are unsuited to local conditions, due to uninformed planning or limited planting-stock availability; even exotic species, known to be detrimental to ecological stability, are sometimes included. Furthermore, post-planting weeding, fertilizer application and monitoring are frequently neglected, often due to budgetary constraints or lack of skilled personnel [2,5]. Consequently, concerns are growing that current

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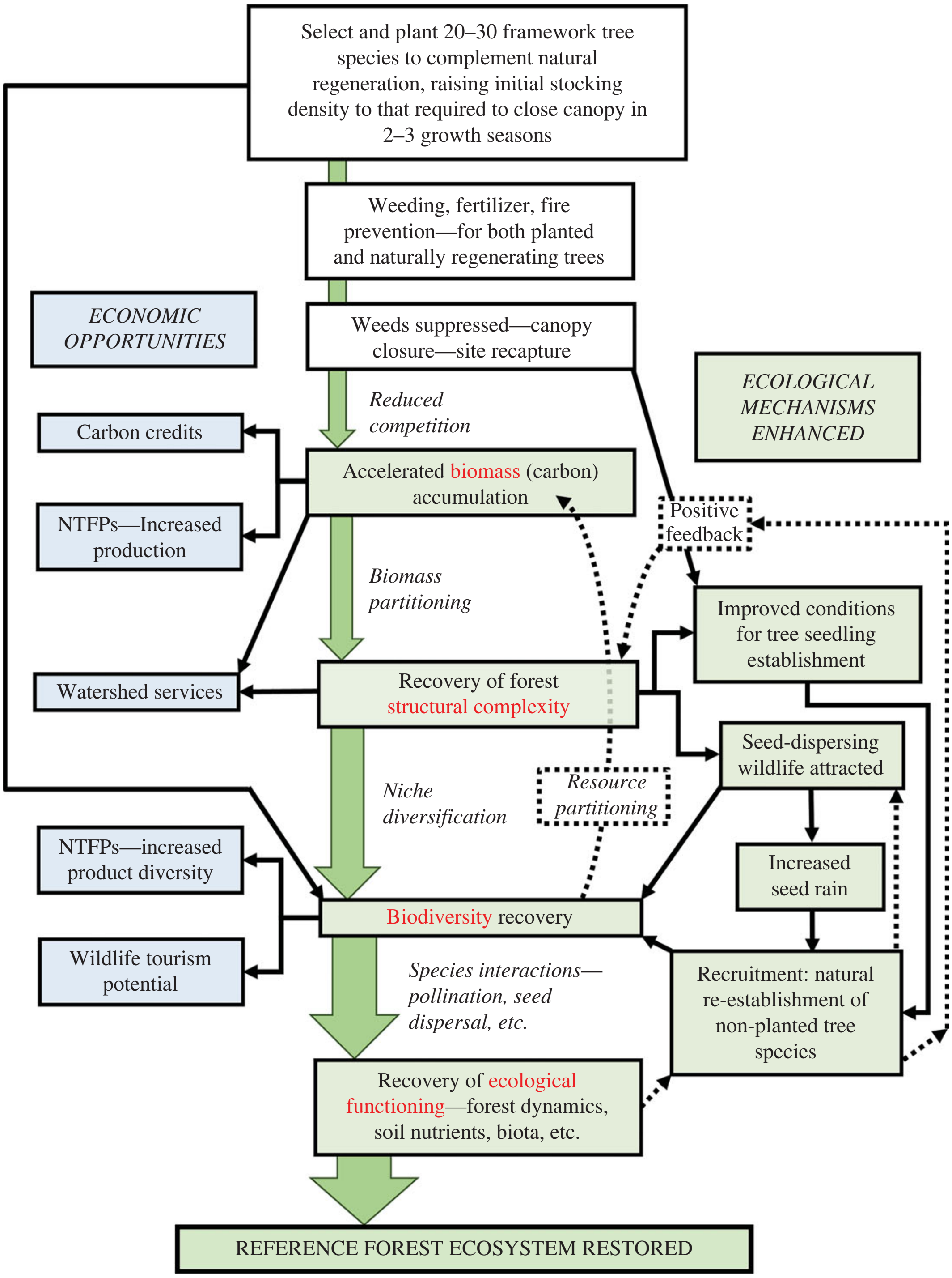

Figure 1. How the FSM accelerates forest-ecosystem restoration. Dotted lines indicate positive feedback loops, by which planted framework tree species intensify key mechanisms of natural regeneration: weed suppression, seed-rain enhancement and creation of conditions conducive to the establishment of recruit tree species. NTFPs stands for non-timber forest products.

mass tree-planting initiatives may fail [6] unless they are based more on established ecological principles [1,7]. With tree planting likely to gain further momentum during the UN Decade on Restoration [8], the need has never been greater for effective techniques to restore biodiverse tropical forest ecosystems.

Here, we examine one such technique—the framework species method or FSM [9,10]. It is one of the least intensive of the so-called 'active' methods [11] of forest restoration, which involves complementing natural regeneration with tree planting on moderately degraded sites, located within seed-dispersal range of remnant forest. It combines species-selection protocols (based on ecological functionality) with optimal management interventions to enhance ecological succession and accelerate the recovery of forest biomass, structure, biodiversity and ecosystem functioning (figure 1).

Although the terms 'FSM' and 'framework tree species' have been in use for 25 years, they have never been formally defined. Therefore, in this review, we clarify the original concept of the FSM and explore how it has been adapted in different countries. We establish its place on a scale of forest restoration techniques, matched with degradation levels (figure 5), identify potential obstacles to its wider use and how they might be overcome. We propose formal definitions for the FSM and framework tree species, so that the technique is used effectively and appropriately, to support the goals of the UN Decade on Restoration (see box 1). This paper is based on the authors' original experiences of

Figure 2. An FSM plot in Queensland, Australia—part of a 32 000-stem planting across 12 sites, ranging from 1 to 5 ha: (*a*) dense cover of Guinea grass (*Megathyrsus maximus* var. *maximus*) at Wooroonooran National Park plot before restoration, 2006; (*b*) the same site 10 years post-planting; (*c*) forest interior after 10 years, showing weed inhibition and understorey regeneration (photos N. Tucker).

Box 1. Definitions

Since the FSM has never been formally and succinctly defined, we propose the following working definitions, based on 30+ years of developing and testing the concept and on review of the studies cited in §5:

The FSM is a technique for restoring forest ecosystems by densely planting open sites, close to natural forest, with a group of woody species, indigenous to the reference ecosystem and selected for their ability to accelerate ecological succession.

Framework species are woody plants, indigenous to the reference ecosystem, selected for restoration projects because of their tolerance of exposed conditions and their collective ability to inhibit herbaceous weeds and attract seed-dispersing animals, thus accelerating recovery of forest biomass, structure, biodiversity and ecological functioning.

developing and testing the technique over more than 35 years in Australia and Thailand, and on cited sources for other countries.

2. Origins

The method originated in tropical north Queensland, Australia in the 1980s. Tree species lists for the region's 13 forest types [12,13] and observations of tree performance at local arboreta provided a foundation for candidate-species selection, while effective propagation techniques for hundreds of indigenous forest tree species were developed in a native tree nursery. Initial field trials from 1985 to 2000, at three sites (11–730 m.a.s.l.) screened out unsuitable species. Subsequent trials focused on optimizing spacing, weeding treatments and the functional and species composition of the planted trees. During the initial trials, recruit seedlings were observed to be more abundant and diverse beneath some planted tree species (e.g. *Homalanthus novoguineensis*) than others, due to their attractiveness to seed-dispersing frugivores. Consequently, further trials focused on testing such 'framework tree species' and those tree species that recruited beside them (figure 2). This allowed the number of tree species planted to be reduced to about 30, while increasing reliance on regeneration, to recover biodiversity.

The FSM's distinctiveness lay in its intensive focus on research-based tree-species selection, using ecologically functional attributes that accelerate forest succession, specifically: (i) those that determine establishment of trees planted on exposed sites (high survival and growth and suppression of herbaceous weeds), and (ii) those that attract seed-dispersing animals (e.g. early production of fleshy fruits, provision of nesting sites, etc.), although not *all* selected species need necessarily combine both functional properties. The reasoning was that the former would result in rapid canopy closure and biomass accumulation, while the latter would bring about rapid biodiversity recovery; these being the primary ecological indicators of successful restoration (figure 1). Thus, the FSM aims to use the minimum numbers of trees and species that are necessary to elicit the maximum possible ecological response (in terms of accelerated recovery of biomass, forest structure, biodiversity and ecological functioning). Lack of adoption of such science-based species-selection rational remains a challenge to widescale forest restoration programs in many countries (e.g. Brazilian Atlantic Forest [14]).

This approach contrasted with contemporary forest-restoration techniques at the time. For example, analogue forestry [15] and rainforestation [16,17] aimed to create novel agro-ecosystems, while including some native tree species to mimic forest structure. On the other hand, the Miyawaki method involved planting a high diversity of native tree species, without rigorous species-selection criteria, beyond that of being ‘main native’ trees [18]. The only other research-based, tree-species selection system for forest-ecosystem restoration at the time was that of Knowles and Parrotta, developed for rehabilitating Amazonian bauxite mines [19]. Their species-selection criteria included fruiting phenology, seed germination, planting stock type and early seedling growth. A two-stage approach was adopted, with pioneers (early successional, light-demanding tree species) planted first, to create conditions suitable for shade-tolerant, late-successional species, planted subsequently—70 species in all. Rapid biodiversity recovery was achieved, with tree-species richness reaching up to 90% that of the adjacent natural forest in 10 years [20]. The FSM differed from this approach, by focusing more astutely on fewer selection criteria, using fewer species (30, compared with 70) and by planting both pioneers and late successional species in a single step.

The term ‘framework species’ first appeared in print in 1995 [21]; first field-trial results were published 2 years later [9]. Since then, framework species have been widely used for restoration projects in Australia’s wet tropics. More than 90% of the 20 most-commonly planted species in the region, listed by Engert *et al*. (table A1 in [22]), are among those originally labelled as framework tree species. The term entered mainstream use in the early 2000s, when it began to appear in restoration textbooks (e.g. [23]).

3. Elements

The FSM comprises a unique combination of elements, specific for the restoration of high-diversity tropical forests on moderately degraded sites, close to remaining forest. Although some of these elements have been incorporated individually into various restoration projects over intervening years [14], the FSM formally integrates them all into a unified generic approach, which applies ecological principles to restoration practices.

(a) Suitability

The FSM is applied for restoring closed-canopy, tropical, forest ecosystems, where the aim is to achieve high rates of biomass accumulation, and recovery of structural complexity, biodiversity and ecological function, as similar to possible to those of the reference forest ecosystem [24] (figure 1). It is most suited to moderately degraded sites (figure 5) near natural forest, that retain viable populations of seed-dispersing animals and where knowledge of the functional attributes of native forest tree species is high.

(b) Low intervention

The FSM takes full advantage of any pre-existing natural regeneration, complementing it by planting the minimum number of trees required to attain a stocking density, sufficient to close canopy and shade out weeds within 2–3 years [25]. Ideal spacing among planted trees and natural regenerants (saplings taller than 50 cm, coppicing tree stumps and trees) depends on tree-growth rates (especially crown expansion, to shade out weeds). The positive relationship between annual rainfall and tree growth is well known, and is particularly strong in the tropics [26]. This seems to have been reflected in the spacing applied by FWM practitioners, which decreases with increasing rainfall (figure 4).

The FSM uses only a small subset of species from the reference forest ecosystem (§4(a)) to initiate biodiversity recovery. As with other restoration methods that involve tree planting, framework trees are planted at the start of the rainy season. This allows maximum time for tree roots to penetrate deep into the soil before onset of the first dry season, thus reducing first-year mortality and the need for subsequent maintenance planting.

(c) Maximizes natural regeneration

The method maximizes natural regeneration in two ways (figure 1). First, it enhances the seed rain. Planted framework trees act effectively as a ‘bait crop’ [21], attracting seed-dispersing birds and mammals from nearby forest to deposit seeds into restoration sites—recovering biodiversity by harnessing the close fruit–frugivore relationships that typify tropical forest ecosystems [27]. Second, the FSM rapidly re-establishes forest-floor conditions, conducive to tree-seed germination and seedling establishment, by eliminating competitive weeds, creating a moist, cool and shady microclimate, and by adding leaf litter and nutrients to the soil surface. Sangsupan *et al.* ([28], p. 1) state that ‘… within 14 years of implementing the FSM, the understory environment had become adequate for regeneration of a wide range of tree species [28]. Regeneration of re-colonizing species confirmed previous reports that the FSM fosters regeneration of species-diverse tree communities’.

(d) The framework species mix

A mix of framework tree species, of varied successional status, is established in a single step to accelerate or even circumvent some of the seral stages of secondary succession.

Experience from early field trials established that the optimal percentage of pioneers to include in the mix was about 15–25% of the total number of planted stems. As mentioned above, species that attract seed dispersers are prioritized. Including short-lived pioneer species results in early, sporadic tree-fall gaps, thus diversifying forest structure and creating light gaps for regenerating species, both of which create a wide range of niches to facilitate broad biodiversity recovery.

Intermediate- to late-successional species comprise most of the remaining mix, particularly those from families that produce attractive fruits (e.g. Araliaceae, Arecaceae, Combretaceae, Lauraceae, Moraceae, Myristicaceae, Myrtaceae, Rosaceae and Sapindaceae). Some may be wind-dispersed canopy species, with limited seed shadows or regenerative capacity in disturbed areas (e.g. *Dipterocarpaceae*). The inclusion of some native Leguminosae species is particularly beneficial where soils are nutrient-poor. Adding indigenous fig trees *Ficus* spp. into the mix is important due to the attractiveness of figs as food for seed-dispersers and the density of their root systems, which greatly facilitate soil ecosystem recovery [29,30]. They are considered to be keystone species, which support frugivore populations when other fruits are scarce. Shanahan *et al*. [31] reported that 1274 birds and mammals, belonging to 523 genera and 92 families, consume figs [31]. Moreover, figs grow in diverse forms: vines, shrubs, rheophytes, epiphytes and canopy trees. In Australia's wet tropics, it is recommended that various *Ficus* spp. constitute about 10% of planted trees [25].

For conservation purposes or to support ecosystem functioning, a few additional species that may not satisfy the framework criteria listed below may be included in small numbers: (i) poorly dispersed large-fruited species (greater than 30 mm in diameter), which are unlikely to recruit naturally [32] due to diminished large-frugivore populations [33], logging or both (e.g. *Eusideroxylon zwageri*) [34]; (ii) rare, threatened, or endangered tree species or local endemics, to support plant-species conservation [35] and/or (iii) keystone species (such as *Ficus* spp. mentioned above), which produce food resources during seasonal shortages, to maintain plant–disperser relationships [27,36,37]. The inclusion of economic or domesticated species is sometimes appropriate, to provide immediate short-term incentives that foster collaboration among local stakeholders—a necessity that is often overlooked during the implementation of forest restoration projects [38]. Methods that adapt several of the FSM principles have been devised to specifically promote use of native tree species and biodiversity recovery in systems aimed at food and timber production, particularly where human population pressure is high, e.g. 'rainforestation' in the Philippines [13,14].

Based on our early trials in Australia and Thailand, a mix of around 30 species works well. Planting more species immediately adds biodiversity and would probably accelerate further biodiversity recovery [39] by attracting a greater diversity of seed dispersers. However, costs of seed collection and planting-stock production increase with increasing numbers of species handled. The need for further research on optimizing the framework species mix is discussed below.

(e) Landscape context specific

With its strong reliance on attracting seed-dispersers, success of the FSM depends on the configuration of forest fragments across landscapes and the presence of functional populations of animals, capable of dispersing seeds from forest to restoration sites. Many closed-forest frugivores are averse to crossing the highly modified environments that surround forest remnants [40]. Therefore, only a small subset of mammal and bird species deposit forest-tree seeds into restoration sites. Some of the most active ones include fruit pigeons and doves (*Ptilinopus* spp.) in Australia and the Pacific, bulbuls (Pycnonotidae) and civets (Viverridae) across southeast Asia, some hornbills (Bucerotidae) in Africa [41], India and SE Asia [42], toucans (Rhamphastidae) in South and Central America [43], fruit bats (*Pteropus* spp.) across Asia-Pacific and northern Australia [44] and some cercopithecine monkeys in Africa [45].

Consequently, the FSM works best where restoration sites lie within the dispersal distances of such animals (i.e. the distances travelled within the gut-passage time of seeds). Capacity to foster biodiversity recovery declines with increasing distance from remnant forest. However, the rate of such decline depends on local conditions. For example, in north Queensland, the FSM works best within 300 m of remnant forest [25]; White *et al*. [46] reported very low seed inputs further than 600 m from seed sources [46]. In contrast, in northern Thailand, diverse recruitment of mostly animal-dispersed tree species has been reported in FSM plots several kilometres from forest [47]; civets are known to disperse seeds 6–8 km from seed sources into restoration sites.

Seed dispersal across landscapes can be enhanced by establishing forest corridors or 'nuclei' to increase linkages among forest fragments. The FSM has been used to establish such forest corridors [48], which not only facilitate seed dispersal across landscapes but also help to maintain genetic diversity in isolated seed-disperser populations by facilitating outbreeding. Where continuous corridors are not feasible, the next best option is to plant 'nuclei'—'small patches of trees that act as focal areas for recovery' [49]. Such nuclei can function as 'stepping stones', allowing seed-dispersing birds to traverse landscapes securely [50]. However, Howe [27] considers the stepping-stone approach as less effective than continuous corridors, because arboreal seed-dispersing animals are often reluctant to travel across open ground between nuclei (e.g. some primates) [27].

(f) Intensive maintenance

Like most forest-ecosystem restoration methods that involve tree planting, the FSM includes intensive maintenance to maximize establishment rates of planted trees over the first two rainy seasons. Before planting, restoration sites are first cleared of weeds without harming residual tree seedlings, live stumps and/or remnant trees. Inadequate pre-planting site clearance results in increased follow-up maintenance and increased risk of damaging the young trees. After planting, repeated weeding is essential until tree crowns overtop the weeds. More frequent weeding is required on wetter sites than drier ones. Weeds may be grubbed out or smothered with organic material [51]. Chemical control with herbicides is effective but controversial. Application of cardboard mulch mats prevents weed-seed germination close to planted trees and is particularly effective on more highly degraded sites ([51], pp. 119–125). Although FSM plots may still contain some weeds 2–3 years after planting, they are usually sparsely distributed and do not compete with the establishing trees. Applying fertilizer both to planted trees and small naturally established seedlings/saplings increases survival and accelerates growth, even on fertile soils. It enables trees to over-top herbaceous weeds and start shading them out within 2 years, thus reducing weeding costs [52]. The recommended dose is 50–100 g of N : P : K 15 : 15 : 15, with three applications in the first rainy season and three in the second rainy season at four- to six-week intervals [53].

4. Framework species selection criteria

Framework tree species are those that are more likely to accelerate natural forest regeneration than a random selection of reference-forest tree species. The various components that contribute towards this functionality are discussed here. While the first two are essential, not all of the others need necessarily be maximal in *all* species planted; rather they should be strongly represented collectively by the mix of species planted.

(a) Indigenous to the reference-forest ecosystem

By definition, framework species are indigenous to the reference-forest ecosystem; exotic species are explicitly excluded. Therefore, where the local flora is not well known, selection of candidate species for trials begins with a survey of remnant reference forest and its successional stages. Published accounts of the local flora and vegetation, as well as indigenous knowledge, are also invaluable for identifying such species.

(b) Tolerant of open conditions

All framework species must be able to persist with high survival and growth rates, in open, exposed conditions. This does not mean that only pioneer tree species are considered. Many tropical-forest canopy-tree species and some under-storey ones are phenotypically plastic, being tolerant of exposure to sunlight, despite growing as shade-tolerant seedlings in mature forest. For example, in tropical Australia and Papua New Guinea, *Elaeocarpus grandis* is a canopy tree in mature forest, but it is also a common pioneer in regrowth; its fleshy fruit make it especially valuable for restoration. In northern Thailand, *Hovenia dulcis* displays rapid growth in open sites, while mature fruiting adults are confined to primary forest [54]. Such plasticity makes such species ideal framework species.

(c) Attractive to seed-dispersing animals

For fostering biodiversity recovery, attractiveness to seed-dispersing animals within a few years after planting is crucial for framework-species selection. Seed-dispersing frugivores are attracted to tree species with fleshy fruits, but other foods such as nectar or high abundance of insects may attract omnivores, which may also incidentally disperse some seeds (figure 1). Provision of structural features that provide perches or nesting sites can also play an important role in attracting seed-dispersers [55]. For example, *Melia azedarach*, planted in framework-species trials in northern Thailand, is highly attractive to birds [56] but not because of its fruits (which are large and woody). Its exceptionally high growth rate creates perching sites far above those of all other planted species, favoured by birds for territorial display.

However, attractiveness varies enormously among tree species, resulting in distinctive seedling communities establishing around each [47]. Those that annually produce fleshy fruits or arillate seeds (preferably at a young age) of high nutritional value are most likely to attract frugivores, particularly narrow-gape (i.e. up to 10 mm [57]) generalist birds (e.g. fruit pigeons (*Ptilinopus* spp.) on *H. novoguineensis* in northern Queensland; bulbuls (Pycnonotidae) on *Prunus cerasoides*, in northern Thailand [56]).

Not only does the success of the FSM rely on fruit–frugivore relationships, it also helps to maintain them. Howe [27, p. 52] notes: ‘adaptations of multiple framework tree approaches have the best chance of preserving or enhancing populations of animal-dispersed trees and their seed vectors…’ [27] (figure 1).

(d) Ability to inhibit weeds

Framework species should inhibit weed growth beneath their crowns by producing dense shade, or by copious production of leaf litter, coarse woody debris or allelopathic chemicals. This is important because weeding is one of the most expensive components of the FSM. Selecting framework species with dense spreading crowns (e.g. *Cecropia*, *Macaranga*, *Trema*, *Homalanthus*, *Gmelina*, *Choerospondias*, etc.) and planting them close enough (figure 4) to initiate canopy closure in 2 years, shades out most light-demanding tropical weeds, except for some vines, which may require ongoing attention. Many tropical trees are allelopathic, i.e. they release chemicals that inhibit germination and growth of nearby weeds (e.g. *Gmelina arborea*). Selection of such species is recognized as an effective tool for weed management during forest restoration projects [58,59].

(e) Ease of propagation

Success of the FSM depends on nursery production of high-quality planting stock of the desired framework tree species: vigorous, disease-free, saplings 25–50 cm tall, weed-free, root-pruned and sun-hardened for at least six weeks before planting. Therefore, ease of propagation is also an important selection criterion. Several practical manuals on how to grow high-quality planting stock of native tropical forest trees in nurseries are available [51,60–62]. Framework species are commonly grown from seed, collected locally from many trees (to maintain genetic diversity). Most fleshy-fruited species can be germinated easily, particularly when seeds are fresh and the pericarp/mesocarp/aril are removed prior to sowing. However, when seed germination is problematic, some species have been propagated from leafy cuttings [30,63]. Nursery experiments to develop efficient propagation techniques are often helpful [64]. A manual of research protocols to improve propagation of framework tree species was published in 2008 [65].

5. Evolving global applications of framework species method

(a) Thailand

The first FSM trials outside Australia were carried out in Thailand by Chiang Mai University’s Forest Restoration Research Unit (FORRU-CMU), following training of the unit’s staff at the Australian sites. The first ecosystem tackled was upland evergreen forest (EGF, *sensu* [66]) in Doi Suthep-Pui National Park, Chiang Mai Province, where the seasonally dry climate was similar to that of the Queensland plots. Working with botanist J.F. Maxwell, characteristic EGF tree species were identified in primary forest and their habitat preferences and altitudinal distributions determined [66]. A phenology study in remnant forest established optimum seed-collection times. Nursery experiments were used to determine seed-storage protocols [67] and production schedules, detailing the most efficient treatments and timings required to propagate planting stock of each tree species by the optimal planting time [68]. Top-performing framework tree species were identified [10] and optimal silvicultural treatments determined [53] in a chronosequence of field plots, planted annually with various species mixtures from 1997 to 2013 in the upper Mae Sa Valley (restor.eco/map/site/chiang-mai-vcnt3-16). Recovery of biomass and biodiversity

Figure 3. (*a*) Upper Mae Sa Valley, northern Thailand May 1998; (*b*) same location after planting framework tree species (3100 trees ha^{-1}), left of track, 15 years old (31 species); right, 9 years old, (76 species); (*c*) forest interior after 21 years. A dense understorey of recruit species (more than 70 measured in 0.46 ha) has developed beneath the closed canopy. Structural diversity has recovered (note woody climbers) and carbon-storage approaches that of mature forest (photos, D. Hitchcock & S. Elliott).

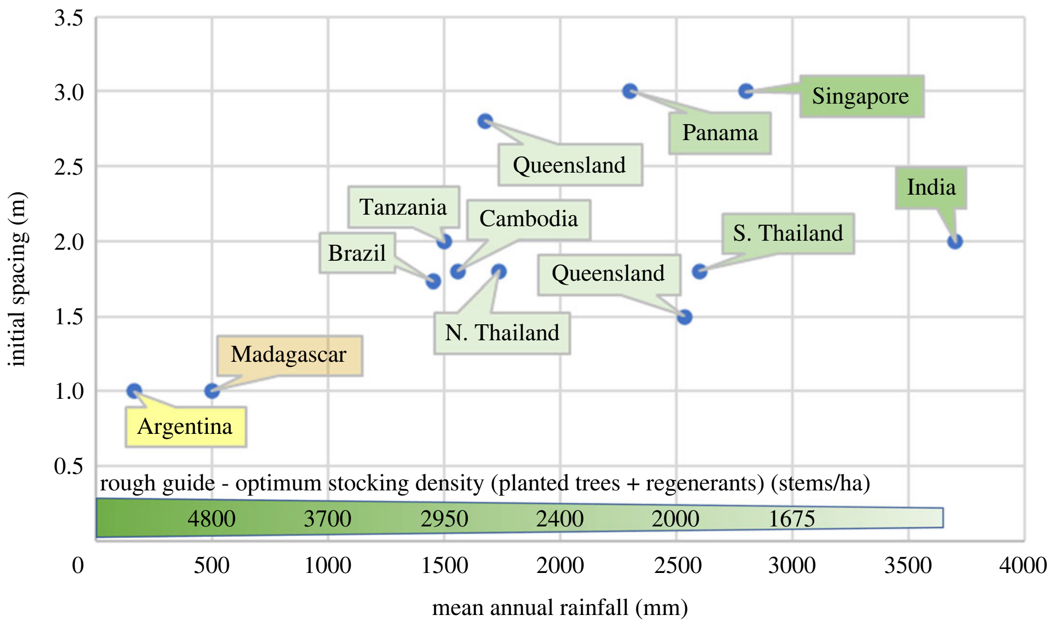

Figure 4. FSM practitioners tend to increase spacing between trees (planted and natural regenerants combined) with increasing rainfall.

exceeded that of control plots and rapidly approached that of nearby remnant forest (figure 3 and table 1). Socio-economic aspects were discussed in Elliott *et al*. [70].

Building on lessons learned from the EGF plots, FORRU-CMU went on to devise equally effective FSMs for lowland deciduous forest in northern Thailand, bamboo deciduous forest in Kanchanburi Province [82] and lowland EGF in Krabi Province [75,83]. The unit also disseminated the concept to China (Yunnan) [84] and Cambodia [76], helping forest authorities to interpret and establish FSMs best suited to the forest types and socio-economic conditions in those countries.

(b) Literature review: emergent lessons

As publications from both the Australian and Thai trials increased, recognition of the FSM as an effective restoration technique grew, although in some cases, use of the term began to diverge from original principles. To examine this evolution, we performed a literature search, using the keywords 'FSM' and 'framework tree species' and sent a questionnaire to the principal investigator of one FSM trial in progress in Tanzania. In total, we reviewed 19 studies in 12 countries from four continents: S. America (Argentina (2), Brazil (2), Panama (1)); Asia (China (Yunan (1), Hong Kong (1)), Cambodia (1), Philippines (1), India (1), Thailand (2), Singapore (1)), Australasia (Queensland (3)) and Africa (Uganda (1), Tanzania (1), Madagascar (1)). Of these, 10 were published accounts of controlled replicated trials and so were included in this review; key findings are summarized in table 1.

Most studies justified use of the term 'FSM' by quoting descriptions of the technique from Goosem & Tucker (14) [21,25], FORRU-CMU publications (7) [10,52] or both (4). In all but two cases, the reference ecosystems of the reviewed studies were diverse tropical or subtropical forest, mostly seasonally dry with one ever-wet site [85]. Exceptions were studies in Madagascar [86] and Argentina [87], which were conducted in arid or semi-arid locations.

Applying the FSM on arid sites is novel, since at the core of the method is a protocol to select a few tree species, from among the several hundred that typically comprise tropical forest ecosystems. Since species richness in most arid ecosystems is low, no such selection procedure is usually needed. Furthermore, 'attractiveness to seed-dispersing wildlife' is an essential characteristic of framework tree species, since a majority of tropical tree species are animal-dispersed; in arid zones, wind-dispersed species predominate [88]. However, where vertebrates constitute an appreciable proportion of local seed dispersers, the concept may have application.

All authors identified biodiversity recovery as the main goal of the FSM. Planting framework tree species was considered complementary to natural regeneration in seven of the studies reviewed.

Regarding selection criteria, all reviewed studies acknowledged that framework tree species are representative of the reference forest ecosystem. A majority adhered to the other four criteria outlined above: tolerant of exposed sites (14); attractive to seed-dispersing animals (13); inhibitory to weeds (11) and easily propagated (12).

In contrast in Uganda, the term 'FSM' was applied to the selection of medicinal plants for home gardens [89]. Even though nursery and field protocols for selecting the 'framework species' mirrored those of FORRU-CMU [10], ecosystem restoration was not the goal. Furthermore, the experiments resulted in some unsuitable species being labelled as framework species e.g. the highly invasive exotic shrub, *Leucaena leucocephala*. Therefore, use of the term 'framework species' was inappropriate in this case.

In Brazil, Turchetto *et al*. described framework species as a small subset of species 'with attributes that are particularly favorable to a given environmental condition' [90]. This broad definition implies that *any* species that grow well on deforested sites are framework species, whether or not they accelerate ecosystem regeneration. This is a departure from the original concept.

Other properties of framework species were mentioned by a few authors. Outside of Thailand and Australia, inclusion of some large-seeded, dispersal-limited species was mentioned in one study in Hong Kong [79], while keystone species were mentioned in eight publications. When the FSM was trialled in fire-prone northern Thailand, fire resilience was added to the framework species selection criteria described above [10] and later in Argentina [87] and Panama [81].

Planting and maintenance procedures varied among the reviewed studies, depending on local conditions. Spacing between trees tended to be closer (1 m) in drier environments, compared with wetter environments (up to 3 m) (figure 4). This may be because tree crowns expand more slowly in dry climates, so close spacing is needed to close canopy and suppress weeds within 2–3 years, whereas in wetter climates, the reverse is true. Closer spacing in drier climates may also compensate for higher mortality due to drought stress. Few of the reviewed studies tested spacing as a treatment. Further trials are therefore needed, to test the stocking densities suggested in figure 4 (derived from spacing data).

The FSM was conceived as a single planting event of both pioneer and later-successional species. In Brazil, Turchetto *et al*. tested FSM variants that included mixed plantations of 100% pioneer species with subsequent enrichment planting of 'more environmentally demanding species' [90]. Such a two-stage approach is a departure from the original FSM concept and requires continuity of management and funding over many years, which are often difficult to guarantee.

6. Discussion

(a) Comparison with other restoration techniques

The FSM sits where 'passive' and 'active' restoration techniques intersect (figure 5) on a scale of restoration practices from least to most intensive, matched with five 'stages of degradation' [52]. For the purposes of this paper, we use the terms 'active' and 'passive' as originally conceived [11]; the former meaning human involvement in tree planting and the latter meaning sole reliance on natural regeneration, although of course, semantically, the latter usually entails a certain amount 'action'. The relative cost-effectiveness of 'passive' versus 'active' restoration approaches has been vigorously debated recently, but to date, few side-by-side comparisons have been performed [91].

Passive restoration works well where the density of natural regeneration is sufficient to form a closed canopy in 2–3 years (degradation stages 1–2 in figure 5). Several levels of manipulation of natural regeneration may be distinguished, from least to most intensive: (i) *spontaneous* natural regeneration [92] (SNR), where no measures are taken to protect, assist or enhance regeneration, (ii) *protected* natural regeneration (PNR), where arresting factors are reduced or eliminated at the site level, e.g. fire prevention, cattle removal, etc. (iii) *assisted* (or accelerated) natural regeneration (ANR), where survival and growth of individual trees are increased by weed control, fertilizer application, mulching, etc. [78] and (iv) *enhanced* natural regeneration (ENR), where the density of natural regeneration is increased by enhancing the seed rain, e.g. by placement of artificial bird perches [93], but stopping short of tree planting. Passive restoration is inexpensive, since there

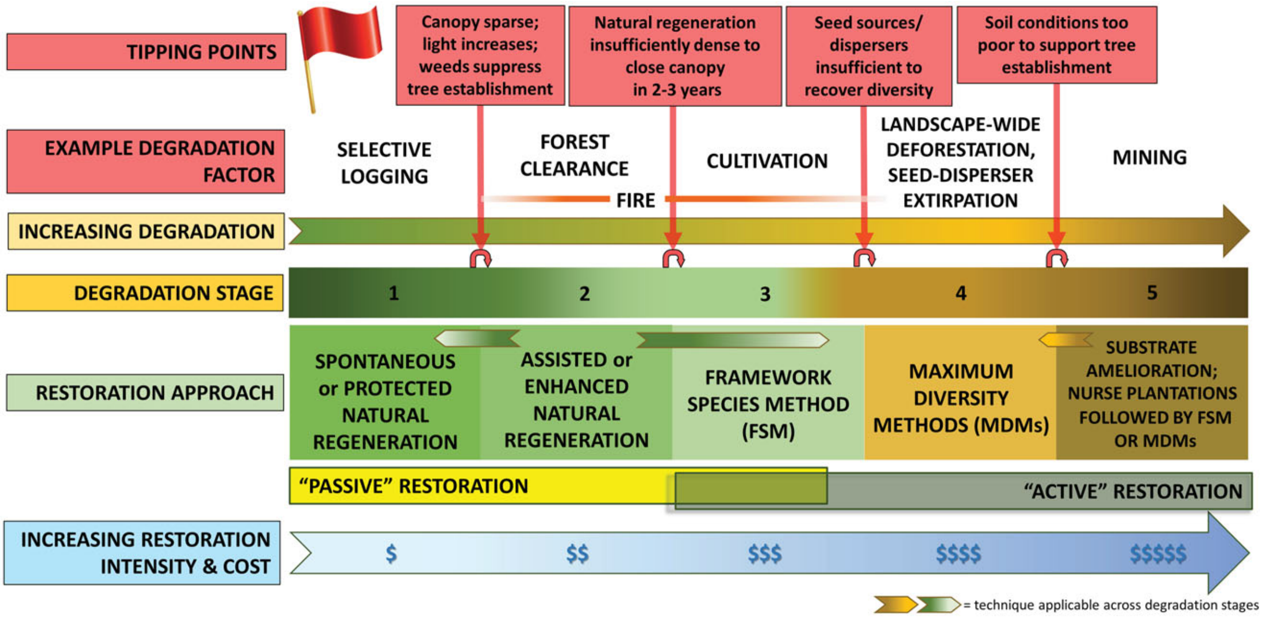

Figure 5. The FSM lies in the middle of a scale of restoration interventions, which become more intensive and more expensive, as initial degradation level increases (adapted from Elliott *et al.* [52]).

Table 1. Key results of published FSM trials that included replication and controls: SST, trials that screened species for FS criteria; FT, field trials that determined the effectiveness of the method at restoring original forest-ecosystem conditions.

location	study type	forest type; rainfall (mm); dry season (months)	results (citation)
Australia	FT	Upland tropical rainforest; 1428–3641; 6	FSM—significantly higher density and diversity of recruit species (72 all life forms/successional stages in 0.25 ha) cf. controls; closed canopy, 6.4–8.7 m in 5–7 years [9].
		Upland tropical rainforest; 1700; 6	Species composition and diversity of planted trees greatly affect tree-seedling recruitment. Grass cover declined as species diversity and canopy cover increased [39].
		Upland tropical rainforest; 1676; 6	FSM outperformed non-planted controls in tree-species recruitment, canopy cover and invasive-species suppression over 21 yr [69].
Thailand North	SST	Upland EGF (seasonally dry); 1736; 5	24 framework species identified [10]; canopy closure in 2–3 years [70]; bird species increased from 30 to 68 species in 5 yr (double that of control) [71]; 73 recruit tree species in 8 years (0.46 ha) [47]; carbon dynamics returned to natural forest levels in 21.5 years [72–74].
Thailand South	SST	Lowland evergreen forests; 2600; 4	30 framework tree species identified, based on nursery experiments, field performance and fruit type [75].
Cambodia	SST	Lowland deciduous forest; 1560; 4	16 framework species identified; optimal fertilizer treatments derived [76].
Philippines	SST	Upland rainforest; 850; 5	21 candidate framework species identified by quantitative measurement in successional forest and grassland [77].
Singapore	SST	Lowland dipterocarp forest; 2800; 0	45 species ranked for restoration suitability by growth rates, contribution to diversity, performance consistency, etc. [78].
Hong Kong	SST	Sub-tropical evergreen; 1400–3000; 5	13 framework species identified from 57 tested. Initial planting of shrubs before planting framework trees recommended [79].
India	FT	Upland rainforest; 3700; 3	80 tree species tested; bird species richness higher in FSM plots compared to forest fragments and coffee plantations [80].
Panama	FT	Seasonally moist tropical forest; 2300; 4	FSM plots had higher stem density at 1.5 years and more stratified structure, cf. conventional reforestation methods. 82% of framework species survived fire [81].

are no tree-nursery costs [94]. However, outcomes are highly variable, depending on many interacting factors, including: initial stocking density, distance to seed sources, seed-disperser abundance and diversity, invasive weeds, fire, land-use history and all the socio-politico-economic factors that influence stakeholder commitment [52,93,95,96]. Nevertheless, the passive approach has successfully restored forest to large areas [92], although compared with tree planting, it is underused [86].

Based on our experiences, we recommend use of the FSM where the density of natural regeneration falls below that required for canopy closure within 2–3 years (stage-3 degradation). This is estimated by a standard rapid site-assessment procedure (see [52], ch. 3 for details), using randomly placed circular sample plots (5-m radius), within which all natural regenerants (saplings taller than 50 cm, coppicing tree stumps and trees) are counted and the number of different species recorded. This allows mean density (per hectare) and confidence limits to be calculated. Involvement of local people in the procedure allows inclusion of indigenous knowledge in the process, such as location of potential seed trees, the presence of seed-dispersing animals, etc. The number of trees to plant is derived by subtracting the recorded regenerant density from that required to achieve rapid canopy closure, with practitioners tending to aim for higher densities in drier areas (where trees grow more slowly) [26] than wetter ones (figure 4), to bring about timely canopy closure. Generally, the number of species planted increases total tree-species richness to around 30, although more appears to be better for biodiversity recovery [39]. Maintenance (weeding and fertilizer application) is applied to both planted trees and natural regeneration.

Since the FSM relies on natural seed dispersal for biodiversity recovery, it does not work well where seed-dispersing animals have been extirpated or become rare and/or where seed sources are too distant (stage-4 degradation). This critical distance depends on the ranging behaviour of the particular seed-disperser species present and landscape context (§3(e)). Under such circumstance, planting far more of the tree species indigenous to the reference forest ecosystem becomes necessary, since many of them are unlikely to recruit naturally. Such 'maximum diversity methods' MDMs (figure 5) [21] involve planting large numbers of tree species, with a much higher proportion of late-successional species and fewer pioneer species (less than 10%), compared with the FSM. Preparation, planting and maintenance are identical to those of the FSM, although maintenance may continue longer, due to slower growth of late-successional species. Perhaps the most well-known MDM variant is the Miyawaki Method [16,18], developed in Japan. Up to 90 tree species are planted at very high densities (up to 3 stems m^{-2}). Extensive soil preparation, addition of soil conditioners and fertilizers, as well as daily watering for 2–3 years are included in the protocol. The high cost of the method limits its use to high-value land, often in urban or industrial settings.

Stage-5 degradation is reached when soil and microclimatic conditions have deteriorated beyond the point at which most tree species can establish without substrate amelioration (e.g. open cast mines). Procedures to improve the substrate's physical structure can include adding top soil, deep ripping and mounding for better drainage and aeration, whereas adding fertilizer, organic materials and green mulching, can improve the substrate's nutrient status and promote recovery of soil fauna and microbiota [97]. Once the soil ecosystem has been revived, 'nurse' trees can be planted to improve the microclimate and add organic matter. *Ficus* species are recommended to open up the substrate physically, while planted legume trees can increase soil nutrients via litterfall. Once site conditions have improved, the nurse trees are thinned and gradually replaced with FSM or MDM species, depending on whether the site is within seed-dispersal range of remnant forest or not ([52], ch. 5).

Establishment costs increase with increasing planting density and diversity [98] and they are highly variable even within each of the five restoration approaches (table 2), because the interventions applied and the labour costs are context-dependent. However, it is interesting to note that FSM costs in Indonesia and Thailand are very similar (around 1–2 US$/tree). Higher costs in Australia are explained by the much higher labour costs there, compared with developing countries. Despite this high variability, table 2 shows that FSM costs lie intermediate between the more 'passive' restoration techniques and the more intensive 'active' ones. It is interesting to note that the range of FSM costs in developing countries (table 2) is very similar to those reported by Rodrigues *et al*. for generic tree-planting approaches to restoring Atlantic Forest in Brazil (3900–5850 US$/ha, adjusted for inflation since publication 2009) [14].

Costs must be evaluated against the value of potential benefits from forest restoration. The estimated total value of forest products and services per hectare of restored tropical forest is estimated at 7732 US$/ha/year ([106], based on 109 studies, adjusted for inflation). Watershed services contribute most (38.8%), followed by climate regulation (32.1%), provisioning services (21.5%) and recreation/tourism (6.2%). All these values are closely dependent on biomass accumulation and biodiversity recovery [1]—two key outcomes of the FSM (figure 1), but conversion of value into cash income depends on the development of accessible markets, supportive governance and capacity building.

Monetization of carbon value is perhaps the most advanced, with carbon credits tradable on international markets. For example, Bradbury *et al*.'s review of 62 restoration projects [107] concluded that 'restoration benefits (e.g. greenhouse gas regulation) tend to outweigh private benefits (e.g. profits from agriculture) driving change to the alternative state'. Even where restoration costs are high (Australia), Mappin *et al*. demonstrated that carbon value alone more than covers the investment needed to implement ecological restoration [108]. Since the FSM is based (i) on the deliberate selection of locally adapted tree species with high rates of survival and growth on exposed sites, and (ii) high planting densities, exceptionally high carbon-sequestration rates are achieved *by design*. In FORRU-CMU's trial FSM EGF plots, increases in above-ground tree carbon averaged 106 tC ha^{-1}, over 14 years [109], almost double the pan-tropical average of 58 tC ha^{-1}, estimated by Silver *et al*. [110], over the first 20 years of tropical forest regeneration.

Sustainable monetization and marketing of such forest values, to create diverse income streams that meet the needs of diverse stakeholders, is therefore the key to achieving socio-economically sustainable forest restoration [107].

(b) Barriers to wider use

Even though the FSM was conceived 30 years ago, its adoption outside of Australia and southeast Asia has been slow, despite its proven effectiveness. This may be due to the difficulty of communicating a novel and somewhat complex approach to

Table 2. Some examples of forest ecosystem restoration implementation costs following methods from least to most degraded site conditions.

degradation Stage[a]	restoration method	country	costs (US $/ha)[b]	note
Stage 1	spontaneous/protected natural regeneration	Thailand	340–395	Fire breaks, patrols and suppression [52]
Stage 2	assisted/enhanced natural regeneration (ANR)	Malaysia	82–117	Vine cutting, selective liberation of economic species. Degraded forest [99].
		Philippines	715	Fire prevention, weed pressing, 500 regenerants per ha. Open weedy sites. [100]
		Cambodia	985	Fire prevention, vine cutting. 6950 regenerants per ha. Dense scrub [101].
		Thailand	2090	Fire prevention, ring-weeding. 974 regenerants per ha. Open weedy sites [101].
		Lao PDR	2135	Fire prevention, vine cutting. 5000 regenerants per ha. Dense scrub [101].
		Thailand	2200	Fire prevention, weeding, fertilizer application and monitoring. More than 3100 regenerants per ha. Open, weedy sites. (FORRU-CMU)
Stage 3	FSM	Indonesia	880	Planting 400 trees ha^{-1} [102]
		Thailand	2200–5700	FORRU-CMU current costs. Planting (up to 3100 trees ha^{-1}), weeding, fertilizer, fire prevention, monitoring.
		Australia	8720–12 280	Termed 'enhancement'. Planting with weed control [103].
Stage 4	maximum diversity method (MDM)	Brazil	821–1706	Direct seeding. 5000 trees ha^{-1}. 57 species [104]
			3976	Tree planting. 2500 trees ha^{-1}. 57 species [104]
			4350	80–100 species 2500 trees ha^{-1}, with deep ripping, added top soil on bauxite mine. [105]
		Thailand	11 030	High density, 43 tree species, with some substrate amelioration (Miyawaki Method) (Toyata, personal communication)
		Australia	17 550–26 280	Termed 'reinstatement'—'high density and diversity of indigenous rainforest tree seedlings' [103]
Stage 5	site amelioration/nurse plantation, then FMS or MDM, as appropriate	Thailand	15 970	Rehabilitation of open cast limestone quarry. Site amelioration + framework species method. 3100 trees ha^{-1} (Siam Cement Group, personal communication)

[a]Elliott *et al*. [52].
[b]Adjusted for inflation to 2021 values.

forest restoration to practitioners and policy-makers. With regard to the latter, the lack of effective 'science-policy interfaces' (SPIs) has long been recognized [111], although progress with developing them has been slow. Some of the factors that we have experienced as impeding development of an effective SPI with regard to the FSM include: lack of clear communication channels between scientists and policy-makers, competing interests amongst forestry research organizations, and more recently, declining regard for scientific knowledge. The latter depends on how scientific information is perceived. Cash *et al*. [112] identified credibility, salience and legitimacy as the three main factors that determine the influence of scientific knowledge on policy-making. Thus, policy-makers' values, beliefs and interests play a dominant role in the incorporation (or lack thereof) of science-based forest restoration techniques, such as the FSM, into policies.

In contrast to government bodies, we have found that non-government organizations more readily take up the FSM, when provided with sufficient information and training. For example, Thailand's leading tree-planting charity, the Rajapruek Institute Foundation [113] has adopted it as standard, whilst various conservation foundations have embraced it to restore the forest habitats of orangutans in Sumatra [114] and lemurs in Madagascar [115]—to name but few.

One impediment to wider uptake of the FSM may be its high initial cost (table 2). Even though the value of restoration outputs usually exceeds costs [107,108], outlays are high in the first 2 years, whereas most of the income from benefits accrue several years later. If start-up costs are funded by loans, then both land-holders and financial institutions become involved in risk-taking—a major deterrent. Therefore, practitioners require easy access to low-interest loans from financial institutions that are willing to share in the risk. Risks are due mainly to uncertainty in such novel markets as payments for ecological services (PES, including carbon), forest products and ecotourism. The creation of equitable, and above all accessible, markets to allow monetization of such outputs is therefore crucial. Such economic considerations are pertinent to all methods of forest restoration, not just the FSM.

A more specific deterrent to wider adoption of the FSM may be the lengthy research required to initiate it, where framework species have not yet been identified. Nursery experiments and field trials, to generate the data needed for selection of effective framework species, may take several years and require both highly skilled personnel and funding. Scarcity of seed sources may also be problematic since, to maintain genetic diversity, seeds must be collected from many individual trees [116]. To some extent, these barriers can be overcome by greater use of indigenous knowledge. Local people usually know which tree species naturally recolonize fallow fields—an obvious short-cut to the identification of candidate framework species—and they may have first-hand knowledge of where seed trees of desired species are located and when they produce ripe fruit.

Identification of candidate framework species may also be accelerated through the use of functional traits—morphological, biochemical, physiological and phenological attributes of tree species that are related to growth, survival and reproduction [117]. Many studies have attempted to relate functional traits with species performance, often for restoration purposes (see [118,119], ch. 10). Betts reported that functional traits are valuable indicators of species performance in FORRU-CMU's trial FSM plots; a combination of wood and leaf traits, that encompass mechanical strength, hydraulic capacity and water storage, were good predictors of the growth rates of prospective framework species [120]. Other studies have linked high survival of planted trees with high wood density [121]; small seed size and large deep crowns with rapid growth; and high leaf-dry-matter content with drought tolerance [122]. The TRY database now makes functional-trait data freely available online (www.try-db.org)—a useful tool for facilitating framework species selection.

(c) Further research

Although the original recommendation of establishing around 30 species, with 20–30% being pioneer species, has produced impressive results, the effects of varying these parameters, particularly on long-term forest succession, has not yet been widely tested in replicated controlled trials. The results of such trials might be beneficial for fine-tuning the FSM or to produce locally suited variants. Furthermore, since framework species vary in their attractiveness to different seed-dispersing animals [47,56], trials to test variations in the species composition of the framework species mix might also provide helpful insight into long term successional trajectories. The relationship between environmental variables (particularly rainfall) and optimal spacing among trees (figure 4), also requires further investigation, as does the development of protocols, to better quantify the tipping points between the FSM and other restoration techniques in figure 5.

At the landscape level, evidence is strong that the FSM works best close to reference forest remnants (as seed sources), where populations of seed-dispersing animals remain viable [46], particularly birds [9]. Several studies have confirmed that rarity of seed trees around restoration sites, as well as inadequate seed dispersal, are the primary limitations to seedling recruitment in FSM trial plots in Thailand, particularly of large-seeded tree species [32,123]. The effects of forest-floor microclimatic conditions in FSM plots are more equivocal. They had little effect on seed germination and seedling survival in the Thailand plots [123], although light levels partially explained growth-rate variability [28]. Several studies have confirmed that from 4 to 8 years after planting, forest floor conditions in FSM plots become highly conducive for seedling establishment of a wide range of tree species, while the seedling communities of non-planted control plots remain species-poor [123]. Ratanapongsai reported that seedlings of 107 tree species established in FSM plots (0.3 ha) within 14 years (double that of control plots, and just over half the number found in reference forest) [32]. However, under-representation of large-seeded species was common to all these studies. In Costa Rica, Holl *et al*. reported that restoration treatment (tree planting versus natural regeneration) is more important than nearby forest cover in affecting the regenerating seedling community (density and species composition), with tree planting being more effective than natural regeneration [124].

Consequently, we recommend further research on measures to increase representation of large seeded species following canopy closure in FSM plots, including trials of direct seeding and supplementary planting of such species. More research on effective seed-dispersal distances would also be helpful for determining the influence of distance from forest remnants on recovery of tree-species richness and composition in FSM plots.

(d) Future directions

Although scientists have well established the technical effectiveness FSM over the past 30 years, the tools needed to overcome the socio-political barrier to its wider adoption have yet to become practicable [14,125]. Therefore, merging scientific with sociological research is necessary to facilitate its wider adoption. For example: what might be the effects of mixing crops with planted trees before canopy closure, particularly those that may promote soil fertility (e.g. legumes) [14]? Although this might initially increase acceptability of the FSM among local stakeholders, it might also delay biodiversity recovery and carbon accumulation, ultimately reducing potential future income from ecotourism and carbon trading. Such trade-offs have not yet been investigated. Recent research in FORRU-CMU's trial FSM plots [109] has revealed that carbon-storage value over the first 14 years is more than 16 times higher (22 215.45 to 25 157.04 US$/ha) than income from the main driver of deforestation in the region: maize cultivation (1347.53 US$/ha)—but such carbon value could only be realized by the creation of a transparent and equitable local carbon market, and the potential macro-economic effects on food production of such a carbon market are yet to be determined. A multidisciplinary approach is therefore essential to resolve such dilemmas.

7. Conclusion

To meet the challenges of the UN Decade of Restoration, a range of tropical forest restoration techniques will be required, based on fundamental ecological principles [1] and matched with appropriate levels of degradation (figure 5) [14]. As the least intensive of the so-called 'active' restoration approaches, the FSM augments natural mechanisms of ecological succession (rather than overriding them) by (i) realizing the potential of natural regeneration, (ii) using planted trees to control weeds, (iii) harnessing relationships between trees and their seed-dispersers to enhance the seed rain and (iv) creating forest-floor conditions conducive to seedling establishment and persistence [28].

Our review revealed generally high adherence to original FSM principles, among those using the term in publications, but a few cases of its misappropriation were identified. This may have been because the concept is usually described in terms of a loose collection of the elements discussed in §3, without ever having been more concisely defined. To retain its usefulness, it is important that the term 'FSM' does not become broadened to mean the planting of *any* tree species that grow well in ecological restoration projects (a trend noted during the literature review). Consequently, we propose the working definitions, presented in box 1, for wider debate.

The review also revealed a paucity of rigorous, replicated, field trials that include (i) FSM treatment plots, (ii) control plots (origin, where natural regeneration proceeds unassisted) and (iii) reference forest plots (target), with data collected just before and after interventions are initiated (baseline) and annually thereafter, at least until regeneration is well underway. Comparing (i) and (ii) determines the effectiveness of FSM interventions above what could be achieved solely by natural regeneration, whilst comparing (i) and (iii) tracks the progress of restoration towards the ideal end-state [1].

Like all other restoration methods, the FSM should be subject to continuous empirical review and adjustment (i.e. adaptive management), as well as objective comparison with alternatives, if it is to contribute significantly to tropical forest conservation and management, and become one of the guiding principles that support implementation of the UN Decade on Restoration in appropriate locations.

Data accessibility. This article has no additional data.

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