Restoration of logged humid tropical forests: An experimental programme at Harapan Rainforest, Indonesia

Authors: Harrison, Rhett D , and Swinfield, Tom

Source: Tropical Conservation Science, 8(1) : 4-16

Published By: SAGE Publishing

URL: https://doi.org/10.1177/194008291500800103

Research Article

Restoration of logged humid tropical forests: An experimental programme at Harapan Rainforest, Indonesia

Rhett D Harrison[1,2,3] and Tom Swinfield[3]

[1] World Agroforestry Centre, East and Central Asian Regional Office, Heilongtan, Kunming 650201, China.
[2] Centre for Mountain Ecosystem Studies, Kunming Institute of Botany, Chinese Academy of Sciences, Heilongtan, Kunming 650201, China
[3] Centre for Conservation Science, Royal Society for Protection of Birds, The Lodge, Sandy, Bedford, SG19 2DL, UK.

Abstract
Restoration of degraded tropical forests can enhance ecosystem service provisioning, improve habitat quality for tropical forest biota and generate income from timber and NTFPs. In Indonesia alone, an estimated 25 million ha of former logging concessions are without current management, representing a huge opportunity for biodiversity conservation. However, currently such forests are typically converted to plantations. Realising the restoration potential of these forests will require viable business models that couple restoration goals with income generation. Unfortunately, understanding of natural succession trajectories and cost-effectiveness of restoration interventions remains poor. We present an overview of research, including three planned experiments designed to test the economic viability of large-scale restoration treatments, in a former logging concession at Harapan Rainforest (98,455 ha), Indonesia. These experiments will address the following questions: (1) Can the selective removal of pioneer trees, including an invasive species, be used to accelerate succession; (2) how does the functional diversity of the planted matrix affect growth and survival of a high value target species; and (3) how does seed density affect recruitment success in direct seeding treatments? Treatments will be applied to large compartments (4~8 ha) to reduce edge effects and simplify management. Monitoring plots (20 x 20 m x 5 reps) within each compartment will be used to assess silvicultural responses, while changes in biodiversity and carbon storage will be monitored at the compartment level. The large spatial scale and high replication of the treatments will establish an experimental platform that will inform many different aspects of tropical forest ecology.

Keywords: biodiversity; carbon sequestration; restoration; SE Asia; logged forest

Received: 7 August 2013; Accepted 13 August 2014; Published: 23 March 2015

Cite this paper as: Harrison, D. R. and Swinfield, T. 2015. Restoration of logged humid tropical forests: An experimental programme at Harapan Rainforest, Indonesia. *Tropical Conservation Science* Vol.8 (1): 4-16. Available online: www.tropicalconservationscience.org

Introduction

Deforestation and forest degradation are often cited as being the primary threats to tropical biodiversity. Approximately 64,000 km^2 of tropical forest are deforested annually [1] and when native forests are replaced with agricultural plantations or exotic tree crops, the loss of biodiversity is substantial [2,3]. However, forests degraded through logging often retain a large proportion of their original diversity and secondary forests regrowing on abandoned agricultural land can recover their biodiversity rapidly, if source populations are available [2,4,5]. Logged and secondary forests comprise an estimated 2 billion ha globally [5] and in Indonesia alone there are an estimated 25 million ha of former logging concessions without current management [6]. Therefore, degraded forests represent an important opportunity for conservation. Logged and secondary forests are also an important carbon pool and sequester carbon more rapidly than mature forests. Forests supply a range of other ecosystem services, including the provisioning of water for human consumption and agriculture, erosion and flood control and local climate amelioration, and the capacity of degraded forests to supply these services is usually enhanced through restoration [5]. Finally, restoration can replenish timber and non-timber forest product (NTFP) resources and thereby, at least partially, justify the retention of forests on economic grounds. Currently, the business-as-usual scenario for exhausted logging concessions is to convert them to Oil Palm or pulp-and-paper plantations [7]. Realising the retention of any substantial proportion of ex-logging concessions under natural forest management will require the development of viable business models that meet restoration goals through generating income from the forest.

If spared from further human disturbance, degraded tropical forests will gradually recover: relatively species-poor forests dominated by pioneer species will be replaced over time by more diverse mixtures of later successional species, and ultimately the climax forest will re-establish [5]. Therefore, one approach might simply be to protect these forests and leave nature to take its course. However, through various interventions it may be possible to enhance the rate of recovery and, moreover, deliberately manipulate forest composition to meet particular management objectives [8]. For example, planting tree species whose populations had been greatly reduced in abundance through harvesting could restore stocks of timber or high value non-timber forest products. Or, planting of fruit-bearing species can enhance the densities of depleted species of wildlife,. Alternatively, to meet the needs of local communities, one might plant enhanced densities of tree species used by these communities [9]. In many cases, forest managers will be required to meet multiple objectives, typically by zoning the management area and applying a number of different treatments according to the specific objectives of each management zone and forest condition [10]. However, despite over a century of silvicultural management of humid tropical forests, understanding of the natural successional processes and the effectiveness of restoration treatments in logged forests remains relatively poor.

Traditionally, tropical silviculture has focused on using timber harvesting to manipulate forest composition, because this was perceived to be the only cost-effective treatment. However, unsustainable timber extraction has reduced the harvestable yields of the vast majority of selectively logged tropical forests in SE Asia to uneconomical levels, leading to their abandonment [7]. Meanwhile, restoration research has tended to focus on highly degraded sites that were completely deforested, such as impoverished grasslands or mine tailings. Knowledge of appropriate interventions for restoring degraded humid tropical forests and, perhaps more importantly, their cost-benefit functions is lacking. In addition, management for multiple benefits requires an understanding of the potential trade-offs between different objectives, such as carbon sequestration, biodiversity conservation and timber or NTFP production.

Although specific protocols vary, potential restoration interventions can be grouped into three basic categories: selective thinning, enrichment planting, and direct seeding [8,11]. Here, we describe three large-scale experiments planned for establishment at Harapan Rainforest, Indonesia to examine the effects of each of these interventions on the rate of forest recovery in terms of timber and NTFP resources, biodiversity values, and carbon stocks. At the time of writing, a large scale selective thinning trial has been implemented, while we expect to start the other experiments over the next 3-5 years. We envisage that monitoring of these interventions will continue for at least 10 yrs, potentially much longer.

Study site

Harapan Rainforest (98,455 ha, UTM 9751000, 311000) is an Ecosystem Restoration Concession in Sumatra, Indonesia (Fig. 1), that straddles the boundary between Jambi and South Sumatra provinces. In 2008 and 2010 the project partners received a 100-yr license to manage ex-logging concessions in South Sumatra and Jambi, respectively. The site is managed through a private company, PT. Restorasi Ekosistem Indonesia (PT. REKI), and a non-governmental organisation, Yayasan Konservasi Ekosistem Hutan Indonesia (Yayasan KEHI). Harapan Rainforest was the first ecosystem restoration concession established in Indonesia and therefore represents an important opportunity for demonstrating the potential of ecosystem restoration as a viable land-use option for Indonesia's logged-over forests.

Monthly mean rainfall varies from 79 mm to 285 mm and the site is therefore classed as aseasonal, although monthly mean rainfall is <100 mm for three consecutive months (Jun-Aug). Mean annual rainfall is 2390 mm. Topography is undulating and, although some steep slopes exist, elevation ranges from just 30-120 m AMSL. The area is dissected by numerous smaller streams and two principle rivers, the Kapas and Meranti. Approximately 60% of the area is covered in Latosols or Red and Yellow Podsols typical of *terra firma* tropical rain forests in this region, while the remaining third is alluvial or swampy (Planosol).

The forest is lowland dipterocarp forest and was extensively logged over the past 20-30 years, both legally under the former concessionaires and illegally. In addition, approximately 20% of the concession area has been converted illegally to small scale oil palm plantations, particularly during the interval when there was no active management (2004-2009) . Data on the number of trees legally harvested was lost in a fire at the logging company's headquarters and no data exist on the number of logs taken illegally. Thus, assessment of forest condition will depend on comparison with historical records from nearby pristine forests [12]. The area is now a complex mosaic of variously degraded forest, with basal area ranging from 0 to ~25 m^2 ha^{-1} (Fig. 2). Most of the forest is covered by an early succession sere, with *Macaranga* spp. (Euphorbiaceae) and *Bellucia pentamera* (Melastomataceae), an invasive pioneer from S. America, which is especially abundant. As these seres are by far the most widespread type of forest in Harapan Rainforest, covering at least 70% of the concession (70,000 ha), this is where our experiments will be conducted.

Despite its highly degraded state, the forest supports an impressive diversity of vertebrates. There are 302 bird species, including 73 of conservation concern. A complete survey of mammals has not yet been completed but among 56 species (not including bats and small mammals), there were 25 species of conservation concern, including charismatic megafauna such as tigers and elephants. The relative inaccessibility of the site and the consequent lack of hunting have probably contributed to the persistence of an intact fauna. Over 600 species of tree belonging to 107 families have been recorded, establishing that the forest is also botanically diverse.

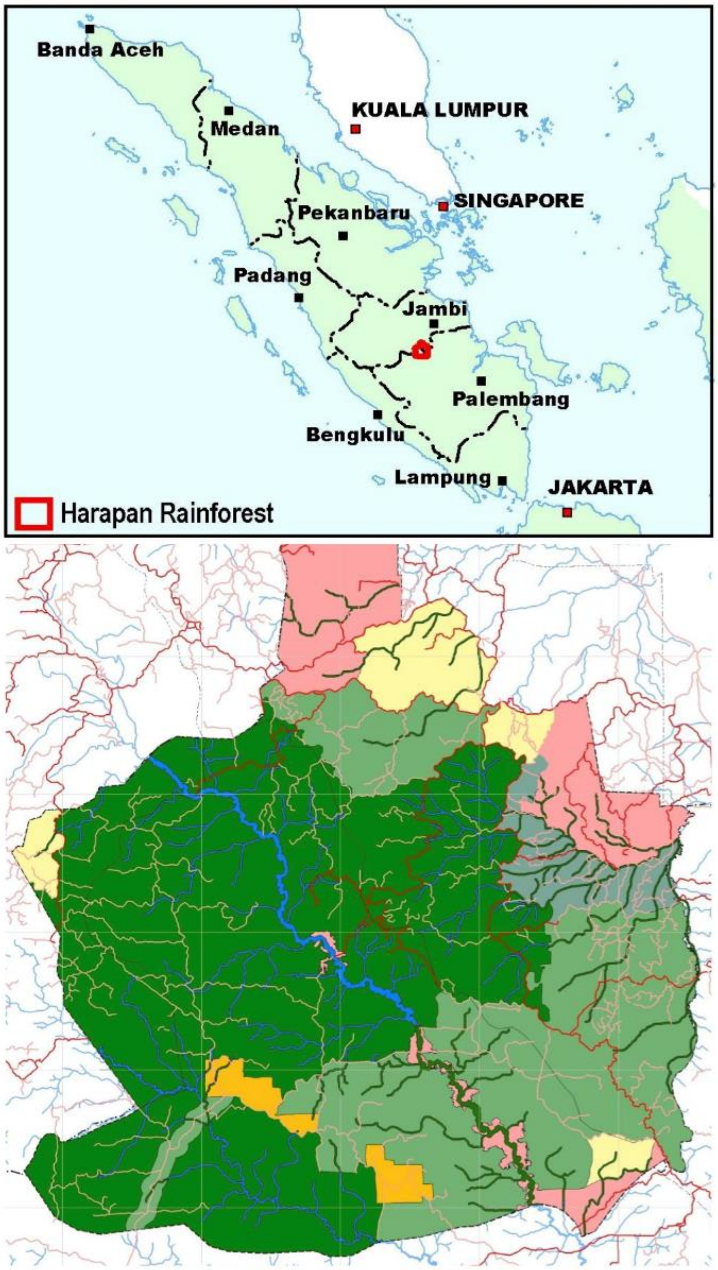

Fig. 1. Location map of Harapan Rainforest and the Harapan Rainforest land-use management plan. Dark green areas represent the conservation forest. Light green represents the production zone, planned for high value timber and NTFP production. Pink zones are the partnership zones for collaboration with encroachment communities

Assessing natural restoration potential

As mentioned above, at least 70% of Harapan Rainforest is covered in low diversity early successional forest dominated by pioneer tree species (Fig. 2). However, the density of seedlings and saplings of later successional species within this pioneer forest varies considerably. Because enrichment planting and, to a lesser extent, direct seeding are expensive, accurately assessing the natural capacity for restoration is critical to determining the appropriate intervention [11].

Traditional methods for surveying forests in Indonesia, and elsewhere in SE Asia, were developed for determining timber volume rather than regeneration potential. For example, the methods currently required under reporting to the Indonesian Ministry of Forestry for the ecosystem restoration license at Harapan Rainforest stipulate a survey of 5% of the area for large trees, but only 0.05% and 0.008% for saplings and seedlings, respectively. Moreover, the method requires the measurement and identification of all individuals within survey transects, which is extremely labour intensive and, therefore, expensive. What is required is a method that enables the rapid quantification of natural restoration potential.

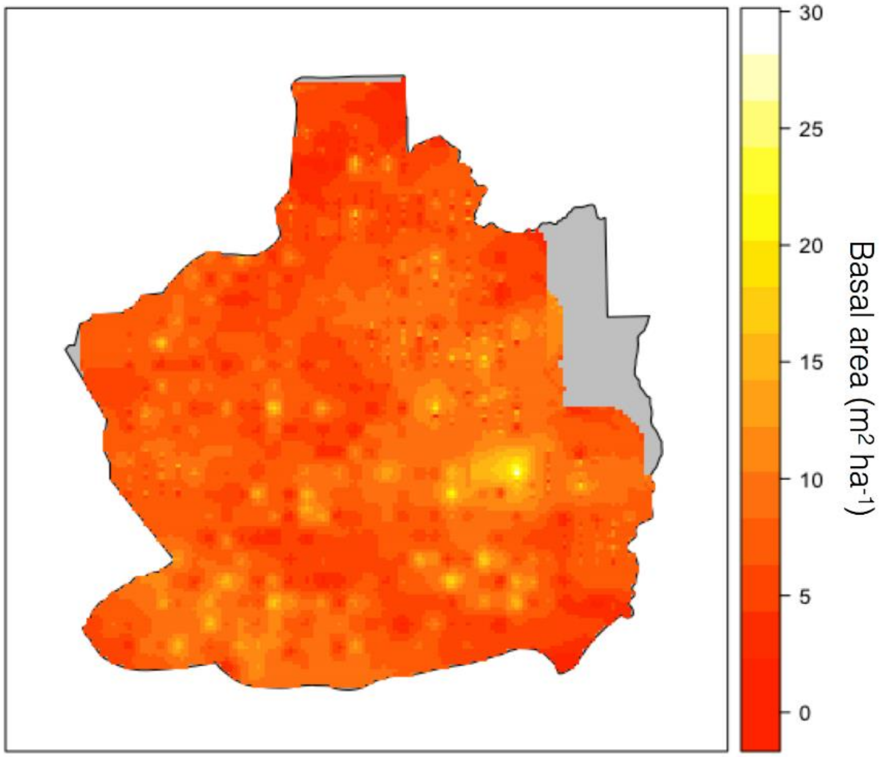

Fig. 2. Basal area map of Harapan Rainforest derived from >1500 0.25 ha plots distributed across the forest.

We are developing methods that employ Unmanned Aerial Vehicles (UAVs) to make rapid canopy surveys of the annual treatment areas (approximately 3000 ha) (Fig. 3). From these canopy images, we plan to map the crowns of distinctive pioneers, including *Bellucia pentamera* and *Macaranga gigantia* (Fig. 4), and assess forest structure (e.g. height and % canopy closure). Other distinctive habitat features requiring special treatment will be identified, such as old skid trails, areas dominated by lianas or bamboos, ponds and swampy areas. Ground based surveys will focus on ascertaining the relationship between the density of the climax species stems in the understory and the parameters measured using the UAVs. This will enable us to predict the natural regeneration capacity over the treatment area and hence determine appropriate interventions. The image processing pipelines and analytical scripts developed will be made available at the end of the project through an open source platform.

Fig. 3. The Unmanned Aerial Vehicle (aka "drone") in action. These remote control planes have a flight range of about 40 km and are armed with a 12 megapixel digital camera. Through an auto-pilot they can be programmed to systematically survey an area of canopy. Photos can be stitched and analysed to produce a map of forest conditions.

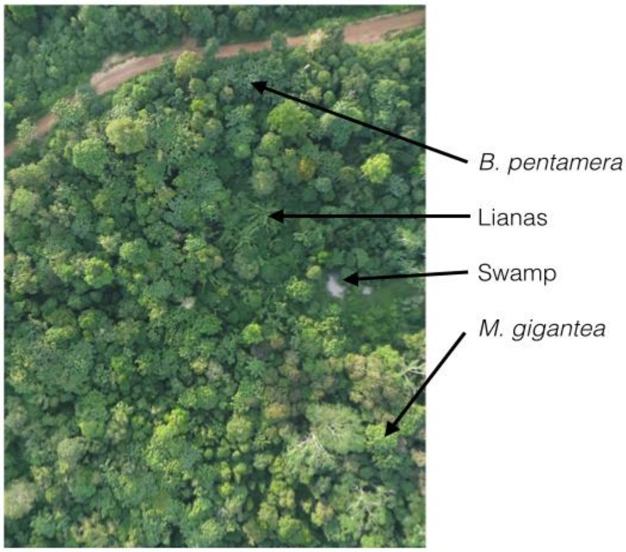

Fig. 4. An image of the canopy taken from a drone. The crowns of distinctive pioneers, including *Macaranga gigantia* and *Bellucia pentamera*, and other features are indicated

Monitoring natural regeneration

To understand trajectories of natural regeneration it is critical to monitor community succession through permanent forest inventory plots. Moreover, because there is a particularly large turn-over among smaller trees in early successional seres, it is important to include trees down to the smallest size classes as is reasonably possible. In addition, to investigate factors determining composition and successional trajectories at a landscape scale, it will be important for us to replicate monitoring plots across the concession. At Harapan Rainforest we plan to set up 25 1-ha monitoring plots following Center for Tropical Forest Science (CTFS) standard protocols [13]. We selected 1 ha plots because these should provide a good point estimate of forest composition and compositional change – a larger number of smaller plots would result in a high level of stochastic variation. As large scale habitat heterogeneity is relatively low within Harapan Rainforest, plot locations will be randomly selected according to a Poisson point process. This should result in a more continuous variation in inter-plot distances than stratified or regular sample protocols would, and hence enable us to better model distance effects. In addition to monitoring trees, we will implement standard protocols to assess soil characteristics and carbon stocks, and the plots will be integrated into our concession-wide biodiversity monitoring program.

Experimental interventions

Experimental design

The proposed experiments are being conducted as part of the ongoing restoration activities at Harapan Rainforest that are required under the ecosystem restoration license. Thus, costs of implementing treatments are covered by restoration budgets. The role of the research is to devise suitable protocols, design experiments to examine cost-benefit functions, and monitor responses within an adaptive management paradigm.

Treatments will be applied at a relatively large scale (4~8 ha), to simplify both implementation of treatments and subsequent monitoring of responses. The relatively large scale of treatments is also beneficial for monitoring biodiversity responses, as the area of forest affected by the treatment is sufficiently large to influence many components of biodiversity, including smaller vertebrates. Silvicultural responses (e.g. the growth and survival of individuals, stem frequencies and total basal area) will be monitored in five 0.04 ha (20 x 20 m) vegetation plots randomly assigned throughout each treatment compartment, but allowing for a 50 m buffer from the compartment edge and between plots. However, monitoring the success of planted seedlings or stems of specific species, may extend outside this area if a larger sample is required.

Plots will be surveyed before treatment, 1 yr follow treatment and at intervals of 3 yrs thereafter. Treatment success and impacts (e.g. removal of pioneers through selective thinning) may additionally be monitored over shorter time intervals. Plot data, including all trees ≥10 cm DBH, with subplots for smaller stems, will enable us to monitor changes in forest structure, competition, tree biodiversity, and above-ground biomass. As responses may depend on abiotic conditions, a soil survey will be conducted, which will also enable us to assess below ground carbon. Other components of biodiversity, such as understorey birds and mammals using mist-netting, and camera traps, respectively, as well as soil mesofauna and arthropods (Malaise trap) using metagenomic techniques [14], will be monitored at the compartment scale. The direct cost of applying management techniques, and where appropriate the costs of seed collection and nursery propagation, will be monitored so that cost-benefit analyses may be performed.

Prior to restoration, a survey will be conducted to assess natural restoration potential using the methods described above. This will be used to assign treatment categories (enrichment planting, selective thinning, direct seeding) to compartments. Clusters of compartments assigned similar treatments will then be grouped into experimental blocks, and blocks will be replicated across the concession. Thus, while each block should be established over a relatively short period of time, it may take several years to implement an experiment. Blocks for different experiments may also overlap. Most large-scale spatial variation derived from differences in soil type and inter-annual variation should be captured by the block parameter. Pre-restoration survey information, such as the density of late successional trees, may also be used as a covariate in analyses. Smaller scale spatial variation within treatment compartments, such as may arise through topography and drainage, will not be controlled for by our experimental design, but this variation should be captured through the replication of monitoring plots. We suggest that the benefits of establishing large-scale treatment areas, which are appropriate both from a management perspective and for monitoring biodiversity responses, out-weigh this loss of sensitivity to relatively small-scale environmental variation.

Selective thinning

Early successional vegetation, when it forms a dense canopy, may suppress the growth of late successional trees [15,16], including many species of higher commercial value. Moreover, because of high propagule pressure, the abundance of pioneer seedlings and saplings can be very high and result in the continual refilling of canopy gaps with pioneers thereby slowing succession. Selective thinning, through the selective mortality pioneer stems within a certain DBH range, may accelerate the succession by enabling saplings of later successional species to reach the canopy. However, excessive opening of the canopy could encourage the persistence of early successional vegetation [17]. Thus, protocols need to be designed that create optimum conditions for accelerating succession.

We will experimentally test the effectiveness of selective thinning through the removal of selected early successional stems. We will test four treatment levels: (i) no removal (control), (ii) 1 m height-10 cm DBH, (iii) 1 m height-15 cm DBH and (iv) 1 m height-20 cm DBH. We aim to achieve a relatively homogenous improvement in the light environment for saplings (1 – 10 cm dbh) of late successional species and the removal of competing pioneer stems. Working within 10 m transects, workers will girdle all early successional trees (primarily focusing on *M. gigantea* and *B. pentamera*) within the appropriate size classes across 8 ha treatment areas. At the time of writing, six replicates of each treatment have been established in one 212 ha block (Fig. 5).

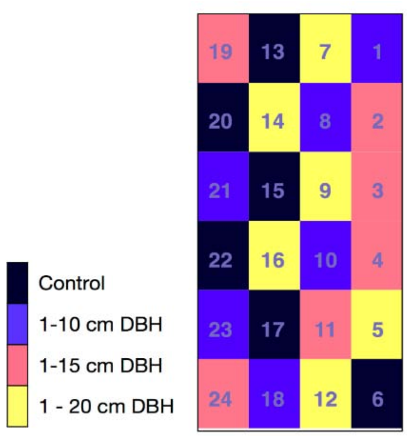

Fig. 5. Plan for the pioneer thinning trial. Colours indicate the different levels of treatment (each 8 ha) and the whole area (212 ha) was blocked from top to bottom because an underlying gradient in forest quality.

Enrichment planting

Following intense disturbance, late successional seedlings may be especially rare, particularly if sites become dominated by highly invasive species, such as grasses or bamboos, or if suitable seed sources are not present [5]. In these areas, succession may be accelerated by the mechanical (or chemical) removal of the dominant species and replanting with selected species. However, such intense treatments are expensive necessitating planting with species that provide both short and long term returns on investment.

Restoration of degraded grasslands, particularly in seasonally dry tropical areas, has led to the emergence of the 'framework species' approach, whereby a set of species is selected to provide a particular suite of functions [18,19]. For example, some species may be selected for rapid growth and to establish canopy cover to shade out the grasses, while others may be selected to provide edible fruits to encourage seed dispersers. However, as currently implemented, the omission of high-value species inhibits commercial application of this method. Moreover, tests of alternative potentially cheaper strategies, such as focusing on a more limited set of species, have not been conducted.

Nevertheless, there is now a large body of research on the role of biodiversity, mostly from grassland experiments in Europe and the USA, which has shown that increased species richness leads to increased ecosystem function. The effect becomes particularly strong when considered over large spatial and temporal scales, as the complementarity in species traits accommodates greater environmental heterogeneity [20,21]. However, it has been pointed out that a large part of the diversity effect may be attributed to complementarity among a few basic functions. Thus, as suggested by the framework species approach, it may be possible to restore forest structure and biodiversity through planting of a limited set of selected species. If species can be selected that are relatively cheap to cultivate, show high survival on planting out, and provide a high return on investment in a relative short period of time, this could substantially increase the cost-effectiveness of enrichment planting for restoring degraded forests.

We will examine how the growth and survival of a high value NTFP species (gaharu, *Aquilaria malaccensis*; Thymelaeaceae) varies with planting density and the species and functional richness of the background matrix (Fig. 6). Gaharu is a fast growing species that, when inoculated with a fungus, yields a high value essential oil. However, it has been found to be very susceptible to insect herbivore damage when planted in dense stands. We will vary the density of gaharu across nine levels from 12 to 353 stems per hectare and the diversity of the background matrix between two levels of species richness; 4 species and 8 species. Matrix species will be randomly selected from a species pool of approximately 20 readily available species to control for species-specific effects. The experiment will be conducted on a 72 ha site that was previously encroached and planted with *Acacia mangium*. The *Acacia* will be removed and then treatments applied to 4 ha planting areas, but a 15 m buffer of matrix plantings will be established around the gaharu density treatments. Thus the area of gaharu treatments will be 2.89 ha. In addition to the performance of gaharu, we will measure the growth and survival of the matrix trees, monitor biodiversity and carbon accumulation.

We plan to extend these experiments to other analogue forest systems in the future and in particular explore the relative importance of functional diversity compared to species diversity.

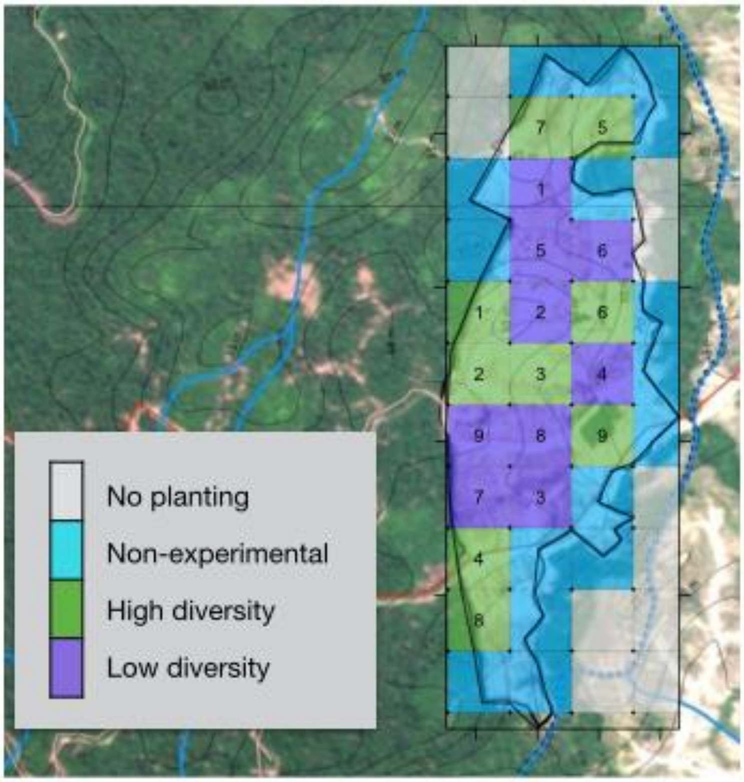

Fig. 6. The planting plan for the gaharu experiment. Treatment areas are 4 ha and the site is a 72 ha formerly encroached area that was planted with *Acacia mangium*

Direct seeding

In the aseasonal forests of tropical SE Asia, flowering and fruiting occurs at irregular, often long, intervals, a phenomenon that has been referred to as general flowering [22]. Because most tropical trees have recalcitrant seeds, this leads to a massive fluctuation in seed supply and for many of the rare or infrequent species it may be difficult or impossible to collect seeds between general flowering events [23]. For enrichment planting this necessitates a large nursery capacity and the maintenance of seedlings in nurseries over a prolonged period, which is expensive [23]. However, as a large numbers of seeds fall near their mother tree, where survival probability is very low, an alternative restoration strategy is simply to collect seeds and sow them over a wider area. This may be particularly valuable where succession is constrained by a low abundance and diversity of seedlings and saplings of later successional species and where seed survival of these species is expected to be good [24].

When a general flowering event occurs at Harapan, we will examine the potential for restoration through direct seeding [24,25,26]. Large numbers of seeds from as wide diversity of species as possible will be collected from nets strung under mother trees. These will be mixed and bagged for transporting to the field, where they will be sown by hand. We will investigate sowing treatments, such as embedding them in a rooting gel, and sowing density. For the latter, we will sow seeds at three densities (high (20 seeds m^{-2}), medium (10 seeds m^{-2}), low (5 seeds m^{-2})) across 4 ha treatment areas, which will enable us to examine the relative effects of seed predator satiation [27] and negative density-dependent mortality [28] on seed survival and seedling recruitment. These treatments and a no-seeding control will be replicated across six blocks (total 96 ha).

Discussion

Because of the expense and difficulties in obtaining management rights, the opportunity to conduct large-scale experiments in ecology is rare. Above-and-beyond their importance for improving our understanding of rain forest restoration, the experiments at Harapan Rainforest will thus provide an important opportunity to investigate many aspects of tropical forest ecology.

Results from our experiments will enable us to construct cost-benefit functions for three principle types of restoration intervention: selective thinning, enrichment planting and direct seeding. Moreover, it will be possible to calculate benefits in terms of different ecosystem functions, including carbon sequestration and biodiversity conservation, and thus assess trade-offs among them and with timber and NTFP production. Such results will enable forest managers to design restoration techniques to enhance biodiversity, ecosystem service provisioning and income generation through accelerating the growth of late successional forest species, including NTFP and high value timber species. Managers will thus be empowered to achieve restoration goals through generating income from the forest.

Implications for conservation

There are an estimated 2 billion ha of logged and secondary forests globally [5]. A conservative estimate of the costs to actively restore these forest is around $US1000 per hectare, or $US2000 billion. Although forests may be left to regenerate naturally in areas where land is marginal and consequently is often abandoned as a result of rural-urban migration [29], in many tropical areas and especially in SE Asia human population growth and pressure on land from plantation industries means that restoration must compete economically with these alternative land-uses. Through enhancing NTFP and high value timber resources restoration is potentially commercially viable. However, the cost-benefit functions of management interventions are currently poorly understood and the trade-offs between income generating activities, such as timber focused restoration, and other ecosystem services, such as biodiversity conservation, are poorly understood. To develop viable business models for forest restoration a much better understanding of the growth and potential yields of timber and NTFP resources in regenerating forests is required. Moreover, to reconcile income generation goals with broader restoration goals forest managers need to understand the extent to which analogue forests, enhanced with NTFP and timber resources, can deliver ecosystem services, including biodiversity conservation. The long-term experiments at Harapan Rainforest will go some distance towards addressing these knowledge gaps and results will directly inform the management and policy environment for ecosystem restoration concessions in Indonesia.

Acknowledgements

The authors are grateful to Harapan Rainforest staff and to the funding agencies that have supported Harapan Rainforest, in particular the Federal Government of Germany through KfW and the Government of Denmark through DANIDA.

References

[1] FAO (2010) Global forest resources assessment 2010. FAO Forest. Rome: Food and Agricultural Organisation of the United Nations. Available: http://www.fao.org/forestry/fra/fra2010/en/. Accessed 4 January 2014.

[2] Wilcove DS, Giam X, Edwards DP, Fisher B, Koh LP (2013) Navjot's nightmare revisited: logging, agriculture, and biodiversity in Southeast Asia. Trends Ecol Evol 28: 531–540. Available: http://www.ncbi.nlm.nih.gov/pubmed/23764258. Accessed 4 January 2014.

[3] Gibson L, Lee TM, Koh LP, Brook BW, Gardner T a., et al. (2011) Primary forests are irreplaceable for sustaining tropical biodiversity. Nature 478: 378–381. Available: http://www.nature.com/doifinder/10.1038/nature10425. Accessed 27 February 2013.

[4] Berry NJ, Phillips OL, Lewis SL, Hill JK, Edwards DP, et al. (2010) The high value of logged tropical forests: lessons from northern Borneo. Biodivers Conserv 19: 985–997. Available: http://www.springerlink.com/index/10.1007/s10531-010-9779-z.

[5] Chazdon R (2014) Second growth: The promise of tropical forest regeneration in an age of deforestation. Chicago: The University of Chicago Press.

[6] Walsh TA, Hidayanto Y, Asmui, Utomo AB (2012) Ecosystem restoration in Indonesia's production forests: towards financial feasibility. Good Business: Making Private Investments Work for Tropical Forests. ETFRN NEWS 54. European Tropical Forest Research Network. pp. 35–41. Available: http://www.etfrn.org/publications/good+business+making+private+investments+work+for+tropical+forests. Accessed 4 January 2014.

[7] Edwards DP, Larsen TH, Docherty TDS, Ansell FA, Hsu WW, et al. (2011) Degraded lands worth protecting: the biological importance of Southeast Asia's repeatedly logged forests. Proc R Soc B Biol Sci 278: 82–90. Available: http://rspb.royalsocietypublishing.org/cgi/doi/10.1098/rspb.2010.1062. Accessed 6 August 2010.

[8] Lamb D (2011) Natural regeneration and secondary forests. In: Lamb D,. Regreening the bare hills. Amsterdam: Springer Verlag. pp. 157–209.

[9] Michon G, De Foresta H, Levang P, Verdeaux F (2007) Domestic forests: a new paradigm for integrating local communities' forestry into tropical forest science. Ecol Soc 12: 1. Available: http://ibcperu.org/doc/isis/8182.pdf. Accessed 5 December 2010.

[10] Sabogal C, Guariguata MR, Broadhead J, Lescuyer G, Savilaakso S, et al. (2013) Multiple-use forest management in the humid tropics: Opportunities and challenges for sustainable forest management. FAO For Pap 173: 1–105. Available: http://www.fao.org/docrep/018/i3378e/i3378e00.htm. Accessed 4 January 2014.

[11] International Tropical Timber Organisation (2002) ITTO guidelines for the restoration, management and rehabilitation of degraded and secondary tropical forests. ITTO Policy Dev Ser 13: 1–84. Available: http://www.itto.int/policypapers_guidelines/. Accessed 4 January 2014.

[12] Laumonier Y (1997) The physiography and vegetation of Sumatra. Kulwer Academic Publishers, Dordrecht.

[13] Condit R (1998) Tropical forest census plots: Methods and results from Barro Colorado Island, Panamá and a comparison with other plots. New York: Springer-Verlag.

[14] Yu DW, Ji Y, Emerson BC, Wang X, Ye C, et al. (2012) Biodiversity soup: metabarcoding of arthropods for rapid biodiversity assessment and biomonitoring. Methods Ecol Evol: 1–11. Available: http://doi.wiley.com/10.1111/j.2041-210X.2012.00198.x. Accessed 12 July 2012.

[15] Paul JR, Randle AM, Chapman CA, Chapman LJ (2004) Arrested succession in logging gaps: Is tree seedling growth and survival limiting. Afr J Ecol 42: 245–251. Available: http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2028.2004.00435.x/abstract. Accessed 4 January 2014.

[16] Goldsmith GR, Comita LS, Chua SC (2011) Evidence for arrested succession within a tropical forest fragment in Singapore. J Trop Ecol 27: 323–326. Available: http://www.journals.cambridge.org/abstract_S0266467411000010. Accessed 4 January 2014.

[17]Dupuy JM, Chazdon RL (2008) Interacting effects of canopy gap, understorey vegetation and leaf litter on tree seedling recruitment and composition in tropical secondary forests. For Ecol Manage 255: 3716–3725. Available: http://linkinghub.elsevier.com/retrieve/pii/S0378112708002387. Accessed 4 January 2014.

[18]Elliot S, Blakesley D, Hardwick K (2013) Restoring tropical forests: A practical guide. Kew: Royal Botanic Gardens.

[19]Goosem S, Tucker NIJ (2013) Repairing the rainforest. 2nd ed. Cairns, Australia: Wet Tropics Management Authority and Biotropica Australia Pty. Ltd. Cairns.

[20]Tylianakis JM, Rand TA, Kahmen A, Klein AM, Buchmann N, et al. (2008) Resource heterogeneity moderates the biodiversity-function relationship in real world ecosystems - art. no. e122. Plos Biol 6: 947–956. Available: http://www.plosbiology.org/article/info%3Adoi%2F10.1371%2Fjournal.pbio.0060122. Accessed 4 January 2014.

[21]Lasky JR, Uriarte M, Boukili DL, Erickson DL, Kress WJ, Chazdon RL The relationship between tree biodiversity and biomass dynamics changes with tropical forest succession. Ecol Lett 17: 1158–1167. Available: http://www.ncbi.nlm.nih.gov/pubmed/24986005. Accessed 4 January 2014.

[22]Sakai S, Harrison RD, Momose K, Kuraji K, Nagamasu H, et al. (2006) Irregular droughts trigger massflowering in aseasonal tropical forests in Asia. Am J Bot 93: 1134–1139. Available: http://www.amjbot.org/content/93/8/1134.full. Accessed 4 January 2014.

[23]Kettle CJ, Ghazoul J, Ashton P, Cannon CH, Chong L, et al. (2011) Seeing the fruit for the trees in Borneo. Conserv Lett 4: 184–191. Available: http://doi.wiley.com/10.1111/j.1755-263X.2010.00161.x. Accessed 26 September 2013.

[24]Tunjai P, Elliot S (2011) Effects of seed traits on the success of direct seedling for restoration in southern Thailand's lowland evergreen forest ecosystem. New For 43: 319–333. Available: http://link.springer.com/article/10.1007%2Fs11056-011-9283-7. Accessed 4 January 2014.

[25]Doust SJ, Erskine PD, Lamb D (2006) Direct seeding to restore rainforest species: Microsite effects on the early establishment and growth of rainforest tree seedlings on degraded land in the wet tropics of Australia. For Ecol Manage 234: 333–343. Available: http://linkinghub.elsevier.com/retrieve/pii/S0378112706004920. Accessed 4 January 2014.

[26]Cole RK, Holl K, Keene C, Zahawi R (2011) Direct seedling of late successional tress to restore tropical montane forest. For Ecol Manage 261: 1590-1597. Available: http://linkinghub.elsevier.com/retrieve/pii/S0378112710003701. Accessed 4 January 2014.

[27]Maycock C, Thewlis, Richard N, Ghazoul J, Nilus R, Burslem DFRP (2005) Reproduction of dipterocarps during low intensity masting events in a Bornean rain forest. J Veg Sci 16: 635–646. Available: http://www.jstor.org/stable/4096759?seq=1#page_scan_tab_contents. Accessed 4 January 2014.

[28]Comita LS, Muller-Landau HC, Aguilar S, Hubbell SP (2010) Asymmetric density dependence shapes species abundances in a tropical tree community. Science (80-) 329: 330–332. Available: http://www.ncbi.nlm.nih.gov/pubmed/20576853. Accessed 23 July 2011.

[29]Wright SJ (2010) The future of tropical forests. Ann N Y Acad Sci 1195: 1–27. Available: http://www.ncbi.nlm.nih.gov/pubmed/20536814. Accessed 3 July 2010.