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Lessons learned from 25 years of operational large-scale restoration: The Sow-A-Seed project, Sabah, Borneo

E. Petter Axelsson [a,*], Kevin C. Grady [b], David Alloysius [c], Jan Falck [d], Daniel Lussetti [d], Charles Santhanaraju Vairappan [e], Yap Sau Wai [f], Keiko Ioki [f,g], Maria Lourdes T. Lardizabal [f], Berhaman Ahmad [f], Ulrik Ilstedt [d]

[a] Wildlife, Fish and Environmental Studies, Swedish University of Agricultural Sciences, Umeå, Sweden
[b] Northern Arizona University, School of Forestry, Flagstaff, United States
[c] Yayasan Sabah Group, INIKEA Project, Tawau, Sabah, Malaysia
[d] Forest ecology and Management, Swedish University of Agricultural Sciences, Umeå, Sweden
[e] Laboratory of Natural Products Chemistry, Universiti Malaysia Sabah, Kota Kinabalu 88450, Sabah, Malaysia
[f] Faculty of Tropical Forestry, Universiti Malaysia Sabah, Kota Kinabalu 88450, Sabah, Malaysia
[g] Department of Environmental Systems Sciences, Musashino University, 3-3-3 Ariake, Koto-ku, Tokyo 135-8181, Japan

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ABSTRACT

While restoration projects globally scale-up to meet the growing demand to restore degraded ecosystems, data on the long-term benefits of restoration are still rare. Here, we describe the lessons learned from the Sow-A-Seed project in Sabah, Borneo: a long-term and large-scale restoration project launched in 1998 with the aim to rehabilitate 18,500 ha of tropical rainforest degraded by logging and forest fires. The project was built from the ground-up, including establishment of essential infrastructure and knowledge creation via trial-and-error. Three restoration techniques were used depending on the level of degradation; 1) Assisted Natural Regeneration (weeding, climber cutting and selective girdling) to promote natural regeneration of late-successional species in the least disturbed forests, and; 2) Enrichment Planting in gap-clusters in moderately disturbed forests, and; 3) Enrichment Planting in rows (i.e, line-planting) throughout heavily degraded forests with no- or few late successional tree species in the overstory. The project includes successful propagation of 92 native tree species including dipterocarps and fruit trees, and planting of over 5 million trees during the last 25 years. Long-term monitoring shows that the mortality rate of planted seedlings is ~15% per year up to 3 years, but decreases to ~2% between years 3–10 and 10–20. One of the largest trees, a *Shorea leprosula* planted in 1998, is now 74 cm in DBH and some planted trees have reached reproductive age and are contributing to natural regeneration. A range of wildlife including orangutans, elephants, hornbills and all five wildcat species in Sabah have been documented in the area. In 2015, the area was classified as a Class 1 protected forest, the highest level of conservation status in Malaysia, and removed from commercial forestry. We highlight that there is much knowledge to be gained by research dove-tailing with operational activities, and we encourage that the lessons learned from operational restoration are shared among practitioners and restoration ecologists. We present 8 key lessons learned from the Sow-a-Seed project.

1. Introduction

With nearly two-thirds of the world's ecosystems degraded to such a degree that it is negatively impacting the well-being of at least 3.2 billion people, and costing >10% of the annual global gross product in loss of biodiversity and ecosystem services (IPBES, 2018), the United Nations declared this decade (2021−2030) as the decade of ecological restoration. Global reforestation efforts, such as those advocated by the Bonn Challenge (www.bonnchallenge.org) and the Trillion Tree Campaign (www.trilliontreecampaign.org/) are expanding at an increasing pace and at great financial expense to restore ecosystem services and recover biodiversity lost from degradation. As the funding available for restoration is increasing, and with ecosystem restoration developing into a multi-billion dollar (USD) industry (Cunningham,

* Corresponding author.
E-mail address: petter.axelsson@slu.se (E.P. Axelsson).

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2008), it has never been more important to share experiences - not only from research - but also the lessons learned by practitioners through operational restoration (Merritt and Dixon, 2011).

Although there is a huge impetus to plant trees to offset carbon emissions, restore ecological function, and secure livelihoods in tropical forest regions using forest and landscape restoration (FLR), evaluating the effectiveness of such activities is often lacking. Operational restoration efforts have typically focused on the numbers of trees planted as a metric for success, and not included monitoring the performance of planted trees over longer timescales (Di Sacco et al., 2021; Banin et al., 2023). A recent review highlights that there is a fundamental lack of long-term data to assess to what extent tree planting contributes to restoration success in the long-term (Banin et al., 2023). There is also a lack of understanding regarding the contribution and effectiveness of tree planting efforts for forests restoration, and if the delivery is successful for restoring ecological and socioeconomic functions expected from restored tropical forests (Hector et al., 2011), but see Philipson et al. (2020). Poor understanding of the long-term contribution of tree-planting, and lack of accurate analysis of cost-benefit trade-offs, limits our ability to design cost effective practices. This is a major shortcoming in the industry, particularly given that tree planting is a relatively expensive intervention (Chazdon et al., 2021).

Furthermore, in highly biodiverse systems, such as tropical forests, reforestation with the aim to rebuild biodiversity of damaged ecosystems is challenged and impeded by the high levels of biodiversity to restore. Understanding patterns of forest succession based on variation in the community composition of the regenerating forest and how this variation impacts diversity of other forest organisms is a major challenge (Axelsson et al., 2022). There are currently also many knowledge gaps in how to propagate and reforest the diverse assemblage of native tree species in large-scale restoration (Jalonen et al., 2018; Bosshard et al., 2021). Basic knowledge on how to produce planting material of native tree species is generally lacking (Jalonen et al., 2018; Bosshard et al., 2021; Grady and Axelsson, 2023) and there are also knowledge gaps on how native trees perform in a restoration context (Gustafsson et al., 2016; Banin et al., 2023). Despite that tropical rainforests can contain hundreds or even thousands of tree species, a vast majority of tree planting projects in Southeast Asia use less than five species (mean of three) (Banin et al., 2023) which is very unlikely to support the broader biodiversity of tree-associated organisms in these ecosystems (Axelsson et al., 2022). There is consequently a great need to develop basic ecological knowledge of a more diverse set of species so that diversified restoration practices can be outlined and implemented (Grady and Axelsson, 2023). Integrating science with practice is critical for evaluating and achieving the multi-functional objectives of large-scale restoration (Merritt and Dixon, 2011).

Here we summarize the major learnings through 25 years of work within the Sow-A-Seed project in Sabah, Malaysia, Borneo. This includes experiences about the important of on-the-ground activities such as seed collection, germination and production of seedlings in the nursery, logistics of out-planting, and building infrastructure, as well as results from research. We made use of our monitoring data to ask three specific research questions:

1) What were the tree survival rates in operational restoration efforts for trees from time of planting up to 20 years, and are there differences in survival between highly disturbed forests where line planting was used and moderately disturbed forests where gap-cluster planting was used?
2) Are there differences among tree species in terms of growth rate and survival that can be used to inform future restoration designs to enhance survival and richness of operational restoration?
3) Given variation in survival and growth, what is the contribution of enrichment planting to tree species richness in operational restoration?

We believe there is much to gain for restoration ecology by dovetailing research with operational activities. By sharing our collective experiences, we can build a body of operational scale reforestation documentation that will guide the development of effective best management practices for tropical forest restoration.

2. Materials and methods

2.1. Background and history

Contemporary to the birth of the field of ecological restoration in the late 20th century (Jordan, 2011) millions of hectares of dipterocarp dominated tropical rainforests on the island of Borneo were severely damaged by wildfire during the 1983 El Niño drought (Woods, 1989). The severity and extent of the 1983 wildfire far exceeded previous fires occurring in the region, e.g., 3.5 million ha of forest were severely damaged in the Indonesian State of East Kalimantan and 1 million ha in the Malaysian State of Sabah. The atypical extent of these fires is attributed to previous logging (MacKie, 1984; Woods, 1989) as a more open canopy increases solar radiative influx and evapotranspiration rates from plants and soils (Goldammer, 2007; Saiful and Latiff, 2019) which in combination with access of logging residues make logged forests more fire prone and the effects more severe (MacKie, 1984, Woods, 1989). Beaman et al. (1985) reported that of the 1 million ha of forested land effected by the fire in Sabah, 85% occurred on logged-over forests and only 15% occurred in primary forest. Furthermore, although the reported effect of the fire on forests varied considerably across the region, some sites suffered up to 94% tree mortality with mortality generally being higher in logged than pristine forests (Woods, 1989).

With the disturbance from the 1983 fire occurring at an atypical large scale, the ecological dynamics of the effected forests were reported as shifting from being governed by small-scale gap dynamic-based regeneration of late successional tree species to undergoing rapid regeneration of weedy vegetation and pioneer species across large areas (Woods, 1989; Nykvist, 1996). In a pristine state, the spatial and temporal heterogeneity of tropical tree-fall gaps plays an important role in maintaining species composition and structure of these forests (Ashton, 1992; Saiful and Latiff, 2019). Furthermore, the regeneration dynamics of these forests are to a large extent also influenced by irregular mast fruiting events taking place every 5–15 years during which a surplus of shade tolerant late successional tree seedlings establish on the forest floor (Ashton et al., 1988; Visser et al., 2011). Mast fruiting can result in tens of thousands of new seedlings per hectare of which only a very small fraction of these (most plausible in the range of ‰ - ‱) will make it into the canopy layer (Ashton et al., 1988, Visser et al., 2011). Given the severity of the 1983 fire and the generally poor dispersal ability of many dipterocarps, Woods (1989) argued that it would exceed one hundred years for the forest to recover to the previous regeneration potential of upper-canopy species and that recovery of pre-fire species composition is very unlikely to ever happen. Due to their sensitivity to disturbance many dipterocarp forests are in high need of restoration (Kettle, 2009).

The 1 million ha of forests in Sabah effected by the 1983 wildfire also included an 18,500 ha of mixed dipterocarp rainforest located in the eastern part of Sabah some 80 km northwest of the town of Tawau (4°36 N, 117°12 E; Fig. 1). This area had experienced previous logging, resulting in lower density of late successional tree species and a more open canopy, together combining to contribute to the occurrence and severity of wildfire affecting the area. With a varying topography (elevational range between 120 and 700 m a.s.l.), forests on steep slopes and at higher elevations were historically less logged and consequently less effected by the fire. Nevertheless, the fire caused thousands of hectares to undergo rapid regeneration of pioneer species across large areas (i.e., as opposed to gap-dynamic regeneration), similar to the effects reported from other areas in Sabah (Woods, 1989; Nykvist, 1996). Fifteen years after the fire, a majority of the area was still heavily degraded and succession tending towards a more diverse state continued to be limited

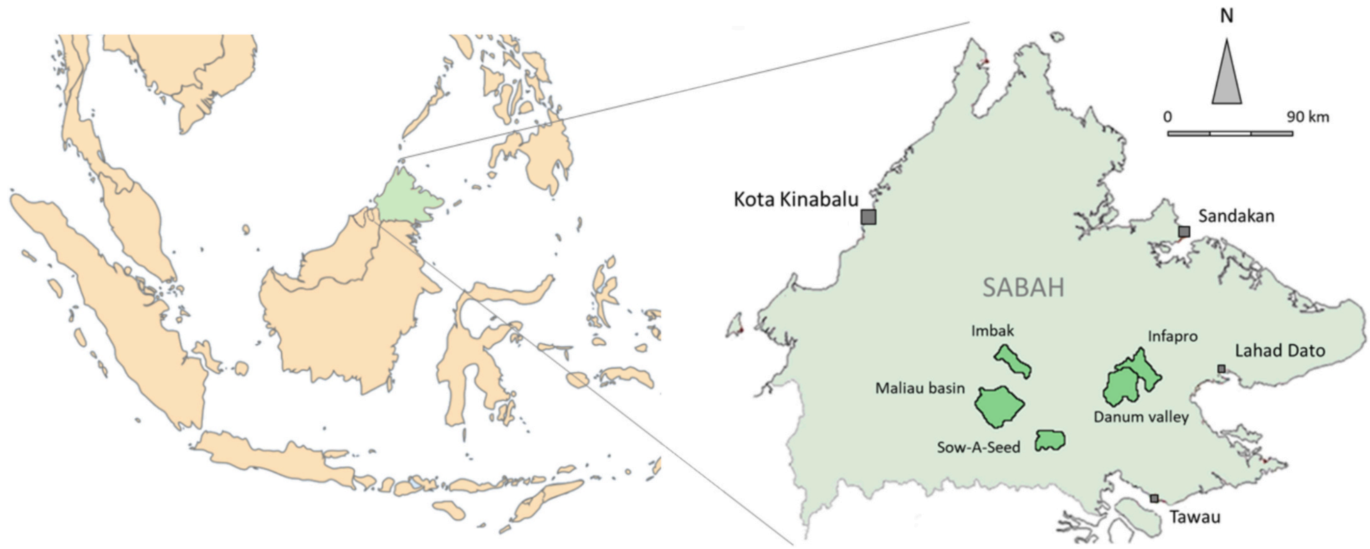

Fig. 1. The location of the Sow-A-Seed project in the State of Sabah on the northeast part of Malaysian Borneo.

by weedy vegetation and a lack of emergent seed trees to support natural regeneration of late successional species.

When learning about the severe and lasting effects of the 1983 fire on the forests of Sabah, a Swedish entrepreneur (CEO of IKEA) teamed up with Dr. Jan Falck of the Swedish University of Agricultural Sciences to test if it was possible to restore a rainforest to a pre-disturbed state. In 1998, the 18,500 ha Sow-A-Seed area was set aside for operational restoration in a cooperation between Yayasan Sabah Group, IKEA and the Swedish University of Agricultural Sciences (SLU). Representatives from Yayasan Sabah, IKEA, WWF, SLU, Sabah Wildlife Department, Universiti Malaysia Sabah and the Forest Research Institute Malaysia, subsequently formed an advisory steering committee. After initiating the project in 1998 with a five-year first phase (Fig. 2), a second and third phase followed (starting in 2004 and 2009, respectively). A fourth and final phase with a larger focus on research commenced in 2015–2020, with site maintenance planned to continue through 2024. The project, is as of 2023, in its 25th year of operation and with restoration operations covering 14,008 ha might make the project one of the largest rainforest restoration projects at that time.

2.2. Project development and design

The Sow-A-Seed project had to be built from the ground-up, including establishment of basic infrastructure such as roads, housing for employees and their families, operational facilities, nurseries, and development of knowledge among field assistants via educational programs. The people working on the project were recruited from nearby villages but a significant number also came from villages far from the project area. The use of foreign contractors, as is typical in plantation forestry operations in the region, were avoided to increase the benefit to local communities. The project has provided daily income for >700 people over its 25 years of operation. About 10% of the people engaged at the time of project initiation (1998) are still working with the project (as of 2023) whereas others have moved on to different jobs elsewhere in Sabah. Some of the current workers are second generation Sow-A-Seed staff. All staff of the project are provided with free housing for their families including electricity and water supply and playgrounds for the children. The village of Luasong has grown during the course of the project; there is a free health clinic and the government-run primary school in Luasong has expanded. School children from the school are taken to visit field camps and learn about nature and why restoration is important.

At the termination of the project a total of 14,008 ha of degraded tropical forest will have been treated with either high diversity enrichment plantings with native trees or with a one-time assisted natural regeneration (ANR) treatment consisting of climber cutting and selective girdling (in Malaysia known as "liberation treatment"). Roughly 4,400 ha of the remaining area was left untreated for natural succession and 100 ha of degraded forest was set aside for scientific experimentation. The largest planted tree, a *Shorea leprosula* planted in 1998, is now >74 cm in DBH and approximately 40 m tall (Fig. 3) and we observe planted trees fruiting and thus contributing to natural regeneration. In 2015, this area was classified as a Class 1 protected forest, the highest conservation status in Malaysia, and can no longer be used for commercial forestry. The Sow-A-Seed project area now serves as a hub for a network of research infrastructure developed to study different aspects of restoration ecology, land-use change, and natural forest management (Box 1).

2.3. Operational activities

2.3.1. Tree species selection

The chief aim of the Sow–a-Seed project was to promote the recovery of biodiversity and facilitate the process of forest succession to pre-

Fig. 2. Timeline of the INIKEA Sow-a-seed project with hectares restored per each of the four rehabilitation phases stretching from 1998 to 2020. The first, second and third phases included a 10-year maintenace period after planting. The fourth phase is followed by a 5-year maintenance period before the restoration project will be brought to an end in 2024.

Fig. 3. A 20-year old *Shorea leprosula* tree in one of the rehabilitated blocks is now 74 cm in diameter at breast height and over 40 m tall. Such planted trees now contribute to the natural regeneration of the area. Photo: David Alloysius.

disturbance levels. Therefore, the project aimed to use as many native tree species as possible for which, due to the near lack of reforestation projects ongoing in 1998, we had little pre-knowledge on the suitability and requirements in a restoration setting. Initially, the project relied on only a few more well-known and often commercially propagated species but the number of species used increased over time as basic knowledge on propagation techniques for a broader range of species developed. The focus was mainly on late successional species with poor dispersal abilities that have a hard time establishing in degraded forests (predominantly dipterocarps and other slow-growing hardwood species) but also included fruit trees of importance for wildlife and seed dispersers. In any given planting block (approx. 30–60 ha) the target objective has been to plant at least 25 different species as a mix of fruit trees, dipterocarps and other late successional tree species. Although the project could have focused on using only species with fast growth and high survival, such an approach would have clearly reduced the overall biodiversity achievable using a more diverse approach. Over the years, 92 different native species have been successfully propagated within the Sow-a-Seed project.

2.3.2. Production of planting material

Supply of planting material is a challenge in large-scale forest restoration (Merritt and Dixon, 2011; Jalonen et al., 2018; Bosshard et al., 2021). In Southeast Asia, it is particularly difficult given the occurrence of sometimes decades long absence of flowering followed by a single year of synchronised flowering (known as mast fruiting) that limits both the amount of seeds and the number of tree species from which seeds can be collected in a given year (Ashton et al., 1988; Visser et al., 2011). To take advantage of the surplus of seeds during mast fruiting years, the Sow-A-Seed project included temporary employment for additional members of the households of permanent staff. This generates extra income for the household from piece-rated employment such as preparing potting bags for the nursery and processing seeds during the mast flowering periods (Fig. 4A). To overcome the uneven availability of seeds across years, the Sow-A-Seed project also implemented a plant propagation scheme that relied mainly on seed collection

Box 1

The INIKEA Sow-A-Seed restoration project is now a Living laboratory of rainforest restoration, a valuable research infrastructure for developing knowledge about tropical forest ecology and restoration during climate change.

A replicated randomized block design at operational scale:

In the last five-year phase (2015–2020) of the project the operational restoration was adjusted to allow scientific evaluation at a larger scale. A 1600-ha area was divided into blocks of between 60 and 100 ha. Within each block the three main restoration methods and their no-treatment controls were assigned to sub-plots randomly, creating a replicated randomized block design. In each sub-plot, we have two permanent sampling plots to measure forest structure and biomass.

Landscape-scale comparison of restoration with industrial plantations and intact rainforests:

In 2018, we established a network of permanent sampling plots in the restoration area where enrichment planting occurred and in non-restored areas, as well as in surrounding Oil palm and Eucalyptus plantations. Using this network we are conducting multifunctional assessments of land-use option from different aspects including carbon storage in biomass and soil (to 1 m soil depth) and different components of biodiversity. Audio recordings capturing the vocalizing animals have been used to compare biodiversity of the soundscape of restored forests and plantations with intact rainforests in nearby forest reserves.

A series of tree species trials:

Within the INIKEA project, we have established a series of common garden trials using multiple native tree species to test for interspecific variation in ecosystem services and functions (Gustafsson et al., 2016; Axelsson et al., 2021; Axelsson et al., 2022), and cascading biodiversity of insects and soil bacteria and fungi (Cowan et al., 2022; Axelsson et al., 2022; Cowan et al., 2023). These trials include a 34-species experiment established in 2008 with native tree species planted at 20 trees per species with accompanying with baseline data of plant growth, survival, and physiological characteristics (Gustafsson et al., 2016). In 2013, we established a 32-species experiment in which replicated trees of the same species were planted across three forest conditions that represented varying levels of forest degradation (Axelsson et al., 2021). Within each forest condition, replicated trees per each species were planted using both line-planting and gap-cluster planting (Fig. 5). The INIKEA sow-a-seed project is also part of a larger network of hybrid planting trails established in 2012 in three locations at INIKEA and a nearby reforestation project called INFAPRO in Danum Valley. This experiment includes 32 tree species planted in clusters of five randomly selected species from the 32 species pool. Clusters are 5 m apart along transects that are 2 m wide. Midlines of planting transects are 10 m apart.

Multi-species common garden experiments:

To examine the extent of intraspecific variation within native tropical tree species, we have established a series of common garden experiments with seed sources collected in 2016 and 2019. These experiments include half-sib families of 14 different dipterocarp tree species collected across geographical gradients and planted in blocks and across forests of different level of degradation. We anticipate that information from these experiments to be valuable for improving the effectiveness of restoration of native forests during climate change (Axelsson et al., 2020), promoting the establishment of native tree plantations rather than exotic ones by identifying superior genotypes, and for basic research on tropical forest ecology and evolution.

Natural forest management experiment in Gunung Rara:

In 1991, Yayasan Sabah and SLU established a forest management experiment in Gunung Rara (SUAS-Experiment), which is located between the INIKEA area and the Maliau Basin forest reserve. The experiment is a replicated experiment across 20 plots of 6 ha treatments testing how different logging practises such as supervised logging and climber cutting can be used to improve stand development and avoid degradation during management of natural forests (Lussetti et al., 2016). Each replicate was measured on 1-ha plots (total 20 ha) before treatments in 1991 and after treatments in 1992. From then, we have re-measured the plots every two years until 2017. This experiment is also part of TmFO (Tropical managed Forests Observatory) a larger network of 32 tropical forest sites in 13 countries (https://tmfo.org/).

during mast fruiting years that were supplemented through wildling collections (e.g., small seedlings regenerating naturally in the forest that are dug up and propagated in the nursery) during non-fruiting years. The wildlings originate from mast fruiting years but can remain small on the forest floor for many years under a shading canopy and be used as a source of planting material. Seed and wildling collections prioritize areas from forest remnants within the project area or in areas immediately adjacent to the project area. A majority of the planting material is thus sourced locally, while locally rare species are collected from within 100 km radius and in extreme cases, from as far as 400 km away. In the later years of the project, empirical testing of progeny from different mother trees was initiated (Axelsson et al., 2020; Axelsson et al., 2023) as a way to develop much needed knowledge about how genetic variation can be used to enhance the outcome of restoration (Grady and Axelsson, 2023).

Seed collection requires proper planning especially for collecting the dipterocarps seeds that are sensitive to desiccation from high temperatures (Corbineau and Côme, 1989). Dipterocarps can shed all their fruits within one to two weeks and therefore, the timing of seed collection is vital. To help predict future mast fruiting events and planning of seed collection, a set of phenological observation plots were developed with 50 individual trees of 32 different species, which were monitored every month for presence/absence of flowering. When >50% of the observed trees are flowering it indicates that mast fruiting will occur within the next coming six months. During seed collection, teams of collectors camp for several days in pre-determined forest sites and collect seeds continuously by visiting every fruiting tree in the area. All viable seeds are collected from the forest floor and put into bags to limit dehydration. All collected seeds are transported to the nursery within 48 h to maintain high viability; seeds are picked up from the camping site every second day and transported back to the nursery for further processing.

At the nursery, the collected seeds are put on germination beds of square wooden boxes filled with sawdust. Regular watering helps maintain high humidity and the germination beds are top-shaded with 70%-shade black plastic sheets (Paranet Waring, Sarlon) to mimic light conditions of the forest floor. The time needed for germination differs between seeds of different species. Most dipterocarp fruits start to germinate within a few days and are often already germinating when collected or arriving at the nursery. Seeds from different species also vary in germination rates and in their susceptibility to fungal infection and insect attack (Appendix 1). *Dryobalanops* spp., *Parashorea* spp., *Shorea* spp. and *Hopea* spp. are among the easiest to propagate; germination time is generally within one week and germination rates are high, i.e., generally over 75% (Appendix 1). The iconic Bornean ironwood, *Eusideroxylon zwageri* (non-dipterocarp), is among the hardest to propagate, germination may take over eight weeks and germination success is generally <50%.

The composition of the potting media used in the nursery was changed several times throughout the duration of the project. At the start, and 10 years into the project, top-layer soil (0–30 cm depth) was collected from the forest and used as the standard growing media. The potting media was later changed to a mixture of topsoil and river sand to improve water infiltration. As the availability of high quality topsoil become scarce, a new experimental media mixture was introduced during phase three. This included a 50/50 mix of mineral soil and compost. This media proved to produce more vigorous plants and became the standard media in the nursery. The compost is produced locally by composting a mixture of grass, saw dust and urea and takes about six months to mature. The potting bags used for most of the seedlings were black plastic bag (polybag) sized 5 cm × 20 cm equivalent to a half litre filled-volume (Fig. 4B). For species with large seeds such as *Shorea macrophylla* and *Eusideroxylon zwageri*, larger 15 cm × 22 cm polybags are used to accommodate their bigger root systems.

Wildings are collected to replenish species stocks as they become depleted due to lack of mast fruiting and use in reforestation, for most species, typically two years after the last mast fruiting. During wilding collection, a team of 3–4 staff visit pre-determined sites early in the morning as collection is prioritized before 10 am to reduce water stress during transportation. It is preferable to collect wildings during rainy days as wet soils make wildings easier to detach and minimize damage to roots. The size of collected wildings is generally kept below 30 cm as larger plants typically suffer significant mortality when they are uprooted. If size is kept below 30 cm, the wildling survival in the nursery is usually above 50%. Some of the fast-growing dipterocarps such as *Shorea leprosula* and *Dryobalanops* spp. have sufficient survival even with wildings of 60 cm tall. The collected wildings are transported and processed in the nursery the same day of collection. Most of the fully developed leaves are trimmed in half to reduce excessive water lost through transpiration. The wildings are planted into pots and kept in high humidity in acclimatization chambers for one to three months to induce rooting (Fig. 4C). When new shoots start to appear, indicating that rooting are on the way, the wildings are moved from the acclimatization chambers to the general nursery stock. The germinated seedlings and wildlings are kept between 1.5 and 2 years in the nursery and receive two applications of 2 g slow-released fertilizer (Agroblen™) at the first month and after a year. There are no chemical fungicides, insecticides or herbicides applied in the nursery or in out-planting. The nursery in Luasong has the capacity to hold up to 500,000 plants (Fig. 4D).

2.3.3. Site preparation

The first step of field operations is a reconnaissance survey to establish boundaries for planting blocks based on the natural features of the area such as rivers, ridges, old logging roads, and the level of degradation that later is used to determine the most appropriate restoration technique for the specific area (see below). The size of planting blocks range from 10 ha to 100 ha. All information, block numbering, area (ha), the proposed restoration technique and the layout of future road serving the blocks, are compiled on a 1:80,000 scale map that assists project activities. The map then directs the layout and construction of roads. In most cases, the layout of roads are directed towards repurposing old logging roads that already exist in the landscape but typically are in need of substantial up-keeping and reconstruction of collapsed culverts and bridges.

With access roads in place, site preparation commences. Site preparation includes marking out reference points by installing 1-m height rot-resistant timber sticks according to the designated planting technique (e.g. line or gap-cluster planting). Planting positions are then marked with 0.3 m tall timber sticks, again according to planting technique. Cutting of lianas and climbers is the standard practice on all blocks, irrespective of liberation or enrichment planting designation, and is performed during the site preparation operation. After climber cutting, most of the top parts of climbers and lianas dry out within a few weeks allowing more light to reach the forest floor and boost growth of naturally regenerating and planted seedlings (Gustafsson et al., 2016; O'Brien et al., 2019). Our observation indicates that most of the cut climbers and lianas will re-sprout after some months and therefore a few rounds of climber cuttings are needed to assist the growth of the planted seedlings more long term.

2.3.4. Restoration techniques

Three different restoration techniques were deployed depending on the severity of degradation. In the least degraded sites as evaluated by a high diversity of dipterocarp trees with some natural regeneration occurring, assisted natural regeneration (ANR) was used that included a one-time climber cutting and removal of selected pioneer tree species (e.g., especially Macaranga species). Such approaches, by removing competition, have proven effective to increase both growth of dipterocarp seedlings (Romell et al., 2008; Lussetti et al., 2016) and larger trees (Lussetti et al., 2016). In moderately degraded sites, indicated by partially open canopy of mainly pioneer species and the occurrence of natural gaps, the gap-cluster planting method was adopted, which is a combination of ANR and enrichment planting. In gap-cluster planting, a grid of 10 × 10 m subplots were overlain across the forest. In each subplot, a naturally occurring light gap was identified for planting (Fig. 5). In each gap, 3–4 seedlings of multiple species were planted and in subplots where no natural gaps could be located, a gap was created via girdling of one or a few larger pioneer trees. The line-planting technique was used in heavily degraded areas as assessed by having an open canopy with abundant understory vegetation. Two-meter-wide lines were laid out throughout the forest with the distance between lines being 10 m. Seedlings were systematically planted every 3 m along the lines (Fig. 5).

2.3.5. Out-planting

The operational out-planting of seedlings is exclusively done during wet seasons to minimize risk of drought and maximize seedling survival. The field staff would prepare planting holes and planting would proceed after three consecutive days with rain. In the early stages of the project, we found that long-distance transportation of seedlings increased seedling mortality to unacceptable levels. To address this, transportation of seedlings in the later phases was directly from the main nursery to the planting blocks only if the transportation was less than an hour. Otherwise, the seedlings were stored in a temporarily constructed nursery located near the planting block, observed for several days to screen for symptoms of stress, and then planted. To facilitate plant growth and survival in both gap- and line-planting, the planted seedlings were maintained via reoccurring weeding, i.e., two to three rounds per year up to year 3, and one to two rounds from year 4–10. At that point the plants were assumed to be large enough to survive in the shade of larger overstory trees and to have limited competition with small-statured understory vegetation.

2.3.6. Cost of restoration

Through the first three phases, stretching from 1998 to 2013, 12,395 ha of degraded forests were restored at a total cost of RM38 million or RM3,000 per hectare. There was a significant cost increase of 43% in phase three (2009–2013) that pushed the per hectare cost to RM4300. The main contribution of the increase in cost was related to operational activities, i.e., increase in salary and higher fuel prices. Previously, the road construction was performed by a road contractor but this cost was reduced by half after the operation was handled by the project's own machines (i.e., crawler tractor and back-hoe loader). In the Sow-A-Seed project, construction and road maintenance accounted for ~30% of the project cost.

Fig. 4. Photos showing some of the steps required for producing ready-to-plant seedlings from seeds in the Sow-A-Seed restoration project in Sabah, Malaysia, Borneo. A) While seeds collected in the forest are germinating in germination beds, staff and families participated in preparing potting bags. This piece-rate activity generates additional income for the household. B) After germinating, seeds are planted into polybags in a 50/50 mixture of mineral soil and compost. Picture showing germinated dipterocarps. C) Satisfactory establishment of wildlings in the nursery requires clipping of leaves to reduce leaf area to approximately 50% and initial growth phase occurring in custom-made chambers for acclimatizing. D) Ready for planting seedlings in the nursery. The capacity for the nursery in Luasong is up to 500,000 seedlings. All photos: David Alloysius.

3. Results and discussion

3.1. Research questions

1) What were the tree survival rates in operational restoration efforts for trees from time of planting up to 20 years, and are there differences in survival between highly disturbed forests where line planting was used and moderately disturbed forests where gap-cluster planting was used?

To assess how plant survival in the operational restoration varies over time and how mortality rate may differ between gap-cluster planting and line planting, we conducted plot-level sampling of tree survival in 10 randomly selected planting blocks. This was done by sampling 10% of the planted lines/clusters at age 3, 10 and 20 years. The results from these surveys show that mortality rate varied across the three periods (Kruskal-Wallis test, $p = 0.001$, statistics = 17.778, df = 2) but not between restoration techniques ($p = 0.778$, statistics = 0.080, Df = 1). Post hoc tests show that the mortality rate of 15% per year over the first 3 years was significantly higher than the mortality rate of ~2% per year between years 3–10 and 10–20 ($p = 0.001$) but that period 2 and 3 had similar mortality ($p = 0.836$)(Fig. 6A). Corresponding to the initial high mortality we found that seedling survival decreased rapidly over the first years and that survival was ~15–25% after 20 years (Fig. 6B).

There are several potential reasons for the initially high seedling mortality in the project area as have also been shown in other studies in mixed dipterocarp forests (Itoh et al., 1995; Nakagawa et al., 2015; Granados et al., 2018; Axelsson et al., 2021). One important factor influencing mortality was evidently herbivory from mammals. We observed porcupines and deer feeding on trees and we also saw wild boar uprooting planted seedlings for making nests, especially during mast flowering period. In nearby Danum Valley, predation by mammals caused up to 44% seedling mortality over three years (Granados et al., 2018). El Niño droughts can also increase seedling mortality over certain years (Axelsson et al., 2021).

Our finding that mortality rate of around 2% for 3–20 year old seedlings is similar to what is reported for trees >10 cm DBH in an natural old growth mixed dipterocarp forest in Pasoh Forest Reserve, mainland Malaysia (King et al., 2006). At an age of 20 years, the average height of surviving planted species in the sow-a-seed project ranges from 5 to 20 m, indicating that the trees are well established and that further mortality, from for example predation by wildlife, should be low. Together this tells us that each hectare of replanted forest contains between 50 and 100 live planted trees after 20 years. These surviving trees have a good chance to help forming the next generation of canopy trees. In undisturbed mixed dipterocarp forests near to the project area, there are around 100 trees per hectare that are larger than 30 cm and <30 trees larger than 60 cm DBH (Forshed et al., 2006). A closed canopy requires about 50–100 trees per hectare reaching above 30 cm DBH. At 20 years, some species of planted trees have reached a reproductive size and are contributing to natural regeneration of the stand.

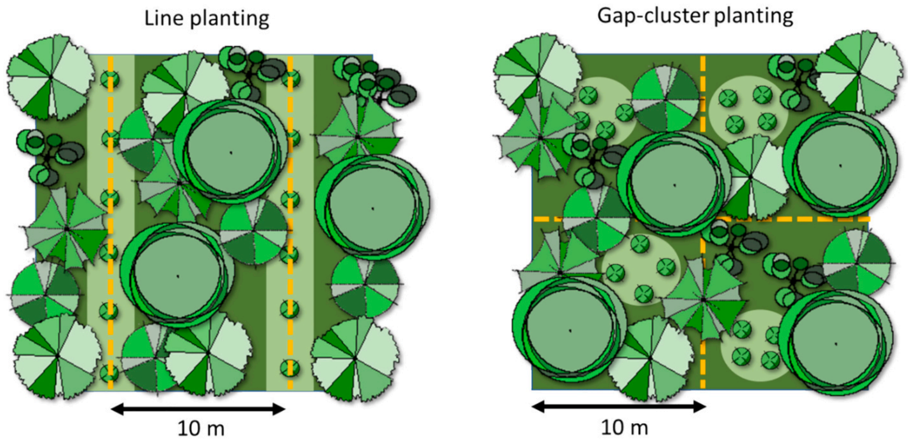

Fig. 5. Principal sketch illustrating the two planting methods used in the Sow-A-Seed project. To the left; line plantings in which 2 m-wide corridors at 10 m spacing are cleared from trees and understory vegetation and planted at 3 m intervals. Yellow dashed lines indicate planting transects where planted trees are indicated by small green circles with an X. All other circles indicate competing vegetation. To the right; gap-cluster planting in which one natural gap is located within each 10 by 10 m square (subplot) and planted with four trees. Light green indicates patches with increased light availability where trees are planted; planted trees are indicated by small green circles with an X. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2) Are there differences among tree species in growth rate and survival that can be used to inform future restoration designs?

To assess among-species variation in survival and growth, we established a planting experiment (November 2008) with the 32 tree species most commonly used in operational restoration in Sabah. By bringing all of these species to one common environment, we could assess interspecific variation in a range of characteristics and traits (Gustafsson et al., 2016; Lindh et al., 2024). We established 40 linear 60–100 m transects, with a distance of 10 m from one another and planted trees 3 m apart with full randomization across tree species. Results from this experiment show that growth varies significantly among species (Gustafsson et al., 2016) and that survival varied between 10 and 100% over 14 years depending on species (Table 1). Species with at least 80% survival after 14 years were *Koompassia excelsa*, *Pentace laxiflora*, *Shorea leptoderma* and *Shorea ovalis*. Species with the lowest survival were *Initsia palembanicia* (10%) and *Shorea parvifolia* (15%). With knowledge about species variation in survival and growth there are possibilities to fine-tune restocking practices, i.e. add more of the preferred but sensitive species and less of the species we know will survive. Nevertheless, the high species variation in survival highlight both a need and potential to enhance restoration outcomes by more in-depth studies on environmental requirements and causes of mortality of different species. Such knowledge would allow site matching for improved survival and growth and for designing of tree species mixture plantings for various and multiple objectives. For example, if we have multiple objectives such as promotion of biodiversity and carbon sequestration we could make sure to plant 100 trees of about 10 species with high growth and survival and then mix in 20–30 more trees that could be more slow-growing, rare and/or important for promoting broader biodiversity (Axelsson et al., 2022).

3) Given species variation in survival and growth, what is the contribution of enrichment planting to tree species richness in restored sites after 24 years?

To assess the contribution of enrichment planting to biodiversity we established 18 survey plots of 1600 m^2 located in the first restored blocks in phase 1. Nine plots were laid out in highly disturbed forests defined as having no more than two large-sized dipterocarps and $>$10% of the basal area made up by macaranga trees. Nine plots were laid out in forests with less disturbance, i.e. at least four large-sized dipterocarps and $<$15% of the basal area composed of macaranga trees. In these plots, we identified all trees (10–50 cm DBH) belonging to the dipterocarp family and noted if they were planted or naturally established. As expected, we found that the contribution of enrichment planting to dipterocarp species richness was higher in the most degraded forests compared to less degraded forests (Fig. 7). In highly degraded forests, the trees introduced via enrichment planting increased dipterocarp species richness of a plot by ~35% and this difference was statistically significant (paired *t*-test; $p = 0.0027$). In less disturbed forests, the trees introduced via enrichment planting increased the dipterocarp species richness in a plot by ~16% but this difference was only marginally significant (paired t-test; $p = 0.0805$). The full importance of tree species diversity for restoring the multiple functions provided by these forests will only be apparent from more long-term studies (Hector et al., 2011).

3.2. Lessons learned

Given that the Sow-a-Seed project was initiated during a period when knowledge of tropical forest restoration was limited, the practices used were largely determined on a "trial-and–error" basis with experiences incorporated into operation through an adaptive management approach. From research and practical experience, we outline 8 key lessons learned that we believe should be considered in future projects.

Lesson One: *Implementation of adaptive management practices for enhanced outcomes.*

We recommend restoration projects to implement adaptive management of operational activities. This may require close monitoring of restoration success, experimental testing of novel practices, but also the implementation of knowledge gained from similar projects. Here, we highlight a few aspects that we feel could be built into management plans for future restoration projects. One key aspect of the Sow-A-Seed project has been that the supply of planting material, which can be major limitation to restoration, can be enhanced from supplementing seed collection via wildling collection. Furthermore, as droughts can reduce survival of planted seedlings (Axelsson et al., 2021) we recommend that planting is conducted only after consecutive days of rain and predominately avoiding expected drought periods. We have also found that hardening off seedlings is often needed to enhance survival especially when longer transportation to planting sites are required. Lastly, repeated weeding until 5 to 10 years after planting is a necessity in this type of ecosystem and light adjustments using, for example, girdling of pioneer trees or liana control can enhance performance of planted seedlings and natural regeneration (Gustafsson et al., 2016; O'Brien et al., 2019). Although we expect these recommendations to be of use for

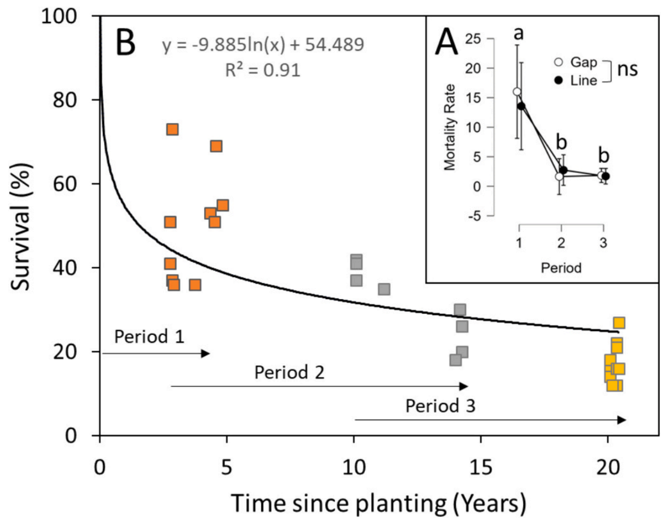

Fig. 6. Temporal patterns of A) yearly mortality rate in gap and line planting (% per year) and B) survival (%) of tree seedlings planted within the Sow-A-Seed restoration project, Sabah, Borneo. Kruskal-Wallis tests show that mortality rate is significantly different between periods ($p = 0.001$, statistics = 17.778, df = 2) but not between restoration methods ($p = 0.778$, statistics = 0.080, Df = 1). Post hoc tests show that period 1 > 2 and 3 ($p = 0.001$), and period 2 = 3 ($p = 0.836$). The regression line is starting from 100% survival at planting and explained variation is optimized with a logarithmic fit.

restoration in comparable systems, they may need to be adjusted to fit local conditions.

Lesson Two: *The question of to-plant-or-not-to-plant is conditional and dependent on the level of degradation.*

Given a general lack of long-term field data (Banin et al., 2023), there has been an ongoing debate about to what extent enrichment planting is an effective restoration technique (Brancalion et al., 2016; de Souza et al., 2016; Crouzeilles et al., 2020). One of the main discoveries from the Sow-A-Seed project is that the choice of restoration techniques and the need to plant depends on the level of degradation (Fig. 8). We have seen that some areas, especially those without remnant late successional trees, clearly do not recover without intervention even 40 years after disturbance, and that planting together with ANR can be a good way to promote succession towards a more diverse state. However, in less disturbed areas with a partially closed canopy and sufficient remnant non-pioneer trees, it could instead have been more cost-effective to use ANR without enrichment planting (Fig. 8). This is similar to findings from restoration projects in Brazil suggesting that the need to restock degraded forests by planting is largely dependent on the level of degradation and that some moderately degraded forest can regrow from ANR even without planting (Brancalion et al., 2016, de Souza et al., 2016, Crouzeilles et al., 2020). For example, Brancalion et al. (2016) found that natural regeneration might be sufficient when the remaining forest cover exceeds 50%. The suitability of the different restoration practices used within the sow-a-seed projects for restoring forest in different states of degradation need to be addressed in future studies. Nevertheless, our results also show that enrichment planting can indeed “enrich” restored forests especially in heavily degraded sites where planted trees contribute to increasing dipterocarp richness by 35% (Fig. 7). Furthermore, Philipson et al. (2020) highlights that active restoration using enrichment planting can benefit carbon sequestration potential of the regrowing forest.

Lesson Three: *The selection of tree species can be adjusted to the aim of the restoration.*

To maximize the biodiversity outcome, the project included the planting of 92 native tree species which is much higher than the average of 3 species currently used in reforestation in Southeast Asia (Banin et al., 2023). Most species were incorporated into the operation without any beforehand available silvicultural or ecological information. In tree species experiments, we found that different tree species vary manifold in germination (this study), growth and survival (Gustafsson et al., 2016; Lindh et al., 2024), financial value (Lindh et al., 2024), and contribution to insect diversity (Axelsson et al., 2022). This is similar to studies in other systems exploring variation among tree species in their contribution to restoring different functions of degraded forests (Elliott et al., 2003; Lu et al., 2017). We can now use this information to adjust how the number of planted seedlings are distributed across species

Table 1
Variation among 34 tree species in survival, height and diameter at breast height (DBH) at 14 years of age growing in a common garden in Sabah, Borneo, Malaysia.

Tree Species	Survival (%)	Height (m)			DBH (cm)		
Baccaurea angulata	70	4.8	±	0.5	4.2	±	0.6
Baccaurea sp	65	5.3	±	0.5	4.0	±	0.5
Canarium sp	50	5.0	±	1.2	3.6	±	0.8
Diospyros sp	60	5.4	±	1.3	4.3	±	1.1
Dipterocarpus conformis	60	7.9	±	1.4	4.8	±	0.9
Dryobalanops keithii	65	5.9	±	0.8	4.2	±	0.6
Dryobalanops lanceolata	70	6.9	±	0.8	4.4	±	0.7
Durio sp	70	5.6	±	1.1	4.1	±	0.9
Heritiera simplicifolia	80	4.4	±	0.6	3.2	±	0.5
Hopea ferruginea	45	6.6	±	1.3	4.2	±	0.8
Intsia palembanica	10	3.5	±	2.1	2.3	±	1.6
Koompassia excelsa	80	4.8	±	0.6	3.1	±	0.4
Mangifera pajang	75	4.3	±	0.7	3.0	±	0.5
Mangifera sp	65	2.1	±	0.2	1.8	±	0.2
Parashorea malaanonan	80	6.0	±	0.9	5.1	±	0.8
Parashorea smythiesii	60	3.8	±	0.4	2.4	±	0.4
Parashorea tomentella	55	7.7	±	1.5	5.7	±	1.2
Pentace adenophora	60	3.8	±	1.2	3.1	±	1.1
Pentace laxiflora	100	7.6	±	1.1	5.3	±	0.8
Shorea beccariana	50	7.4	±	1.4	6.7	±	1.5
Shorea faguetiodes	50	5.2	±	0.6	4.4	±	0.9
Shorea falciferoides	65	5.7	±	0.8	4.0	±	0.7
Shorea fallax	70	8.0	±	1.2	7.5	±	1.4
Shorea leprosula	30	13.9	±	3.4	12.3	±	3.2
Shorea leptoderma	80	7.9	±	0.6	5.5	±	0.6
Shorea macrophylla	70	8.2	±	1.5	8.1	±	1.9
Shorea macroptera	55	8.2	±	1.0	8.3	±	1.3
Shorea ovalis	80	7.9	±	1.0	7.1	±	1.2
Shorea parvifolia	15	14.3	±	4.0	15.3	±	6.1
Shorea pauciflora	60	3.3	±	0.4	2.7	±	0.5
Shorea platyclados	30	11.2	±	2.2	9.8	±	2.6
Shorea xanthophylla	65	4.5	±	0.5	3.0	±	0.4
Sindora beccariana	50	4.9	±	1.2	3.2	±	0.9
Walsura pinnata	70	3.7	±	0.3	2.2	±	0.3

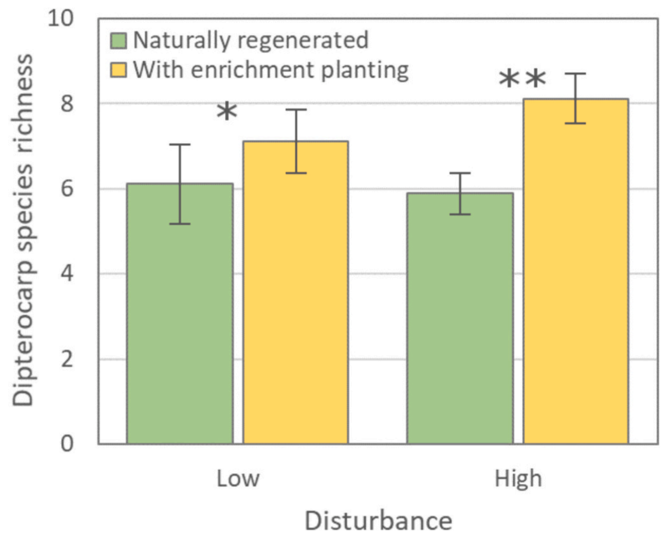

Fig. 7. Species richness of dipterocarp trees larger than 10 cm DBH in a tropical rainforest restored via enrichment planting in the Sow-A-Seed restoration project in Sabah, Borneo, Malaysia. Full green bars represent richness of the remnant stand and hatched yellow bars represent the contribution of enrichment planting to dipterocarp species richness (±SE). A single asterix above paired bars indicates statistical significance at the alpha 0.05 to 0.10 significance level and a double asterix indicates statistical significance at the <0.05 significance level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

depending on the restoration goal (e.g., biodiversity, carbon sequestration, financial return, etc.) or a combination of different restoration goals. With improved knowledge of performance of different species in different environments, it would also be possible to compensate for high mortality in some type of habitats by planting in higher densities, whereas other areas could have benefitted from planting more fast-growing trees in order to close the canopy earlier. We are also investigating how functional traits of species can be used to understand the ecosystem functions that different species deliver (Gustafsson et al., 2016; Axelsson et al., 2022; Lindh et al., 2024). Better knowledge regarding functional variation among different tree species could not only benefit restoration projects in the region, but also has potential to inform commercial forestry and agroforestry where there is a desire to incorporate native species and the ecosystem values they provide.

Lesson Four: *Tree diversity matters for broader biodiversity.*

Restoring forest ecosystems can be much more than re-establishing forest biomass, a closed canopy, or a tree species composition similar to pre-degradation state. Goals of restoration may also include restoring broader biodiversity especially in this era of species loss known as the 6th mass extinction (Barnosky et al., 2011; Ceballos et al., 2015) and the insect apocalypse (Montgomery et al., 2020). Mixed dipterocarp forests are known to promote some of the most species rich communities on earth including a wide array of diverse taxa such as insects (Sakai et al., 1999; Axelsson et al., 2022), birds (Engstrom et al., 2020) and mammals

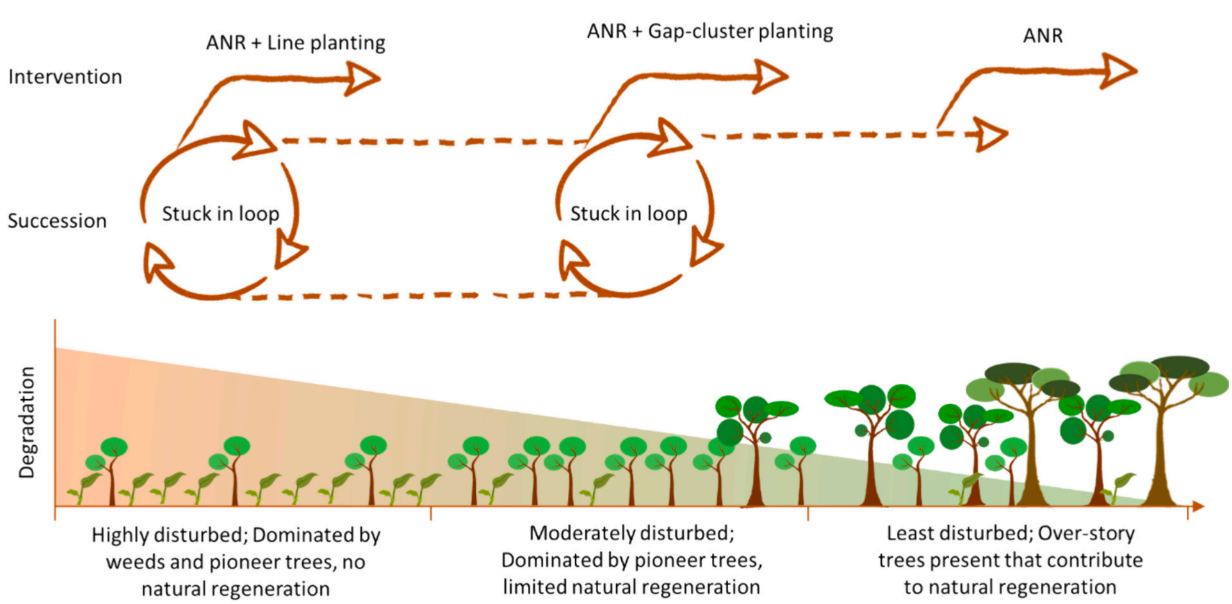

Fig. 8. Three restoration methods are used within the Sow-A-Seed project area depending on the level of degradation. In highly disturbed sites, classified by a dominant herbaceous plant community and pioneer tree species, assisted natural regeneration (ANR) with line planting is used to assist rehabilitation. In intermediate levels of degradation, indicated by an abundant canopy of pioneer trees such as Macaranga spp., ANR is combined with gap-cluster planting to make use of already existing gaps in the canopy. In less disturbed sites, indicated by a quite diverse community of late successional tree species and the occurrence of natural regeneration, the establishment is assisted via ANR.

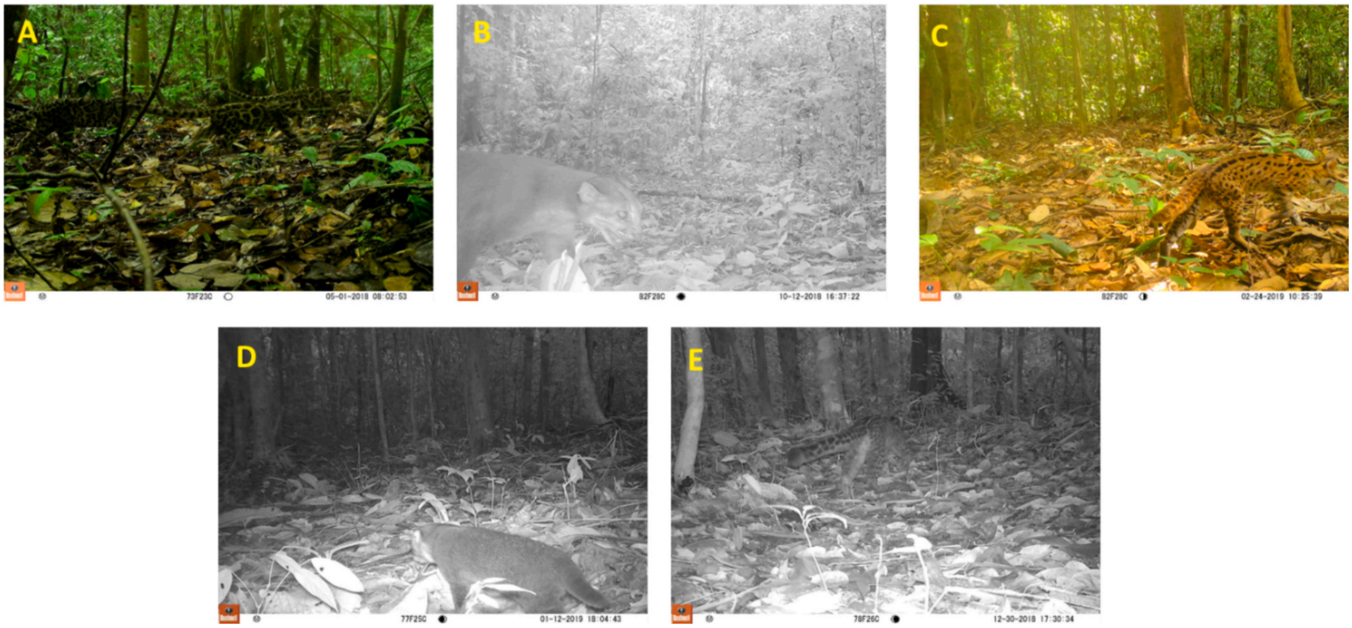

Fig. 9. Photos from camera trapping show that the restored Sow-A-Seed area is attracting a variety of wildlife, including all of the five wildcats of Sabah; A – *Prionailurus bengalensis* (Clouded leopard), B – *Catopuma badia* (Bay Cat), C – *Pardofelis marmorata* (Leopard Cat), D – *Neofelis diardi* (Flat Headed Cat), E – *Prionailurus planiceps* (Marbled Cat).

(Charles, 1996; Chapman et al., 2018), many that are under threat from habitat loss and degradation. Understanding to what extent different tropical tree species vary in their support of biodiversity is generally poorly known but such knowledge could help in selection of "foundation tree species" for use in reforestation (Axelsson et al., 2022). Despite that many previous studies indicate that insects in tropical forests tend to be hosts generalists, suggesting that tree species could be hosting similar communities (Basset, 1999; Novotny et al., 2002), we have learned that different tree species in mixed dipterocarp forest do vary in their contribution to broader biodiversity. A case study with beetles (coleopteran) revealed that beetle richness in the canopy of planted trees varied threefold between species. We also estimated that it would take at least 48 different tree species to cover most of the diversity of the assessed beetle community (Axelsson et al., 2022) which is much higher than the average of 3 species currently used in reforestation in South East Asia (Banin et al., 2023). Species traits are essential, e.g., selecting mainly the fasted growing species to maximize carbon capture may not be the best option if the goal is to promote biodiversity (Axelsson et al., 2022). Similar studies are underway evaluating the impact of tree species diversity on soil micro-floral composition (e.g. bacteria and fungi) and how that diversity feeds back to influence growth and survival (Cowan et al., 2022; Cowan et al., 2023).

Lesson Five: *Genetic variation of native trees is a neglected potential for native reforestation.*

Confounded by the great diversity contained in tropical forests, genetic research of tropical tree species lags far behind research in non-tropical systems (Grady and Axelsson, 2023). There is a growing need to assess how genetic variation of native tree species can be utilized during reforestation (Thomas et al., 2014; Prober et al., 2015; Gregorio et al., 2017; Jalonen et al., 2018; Axelsson et al., 2020) and for pre-adapting restored forests to the climates of the future (Axelsson et al., 2020). Pioneering work initiated within the Sow-A-Seed project highlights that there is a great genetic potential within tree species that can contribute to enhancing the success of restoration projects (Axelsson et al., 2020; Axelsson et al., 2023). We have shown that the choice of seeds from different mother trees alone might affect the initial height growth 2–3 fold (Axelsson et al., 2020, Axelsson et al., 2023), and that such variation in some instances can be predicted by the elevation of the source population (Axelsson et al., 2023). More long-term research is needed but for now we suggest that restoration projects try to maximize genetic variation by seed sourcing from different populations and mother trees (Axelsson et al., 2020; Grady and Axelsson, 2023). For future development, we have started collecting genetic material in "common garden" field trails, which can also serve as a biobank of rare genetic material for future restoration needs. Such research has high potential to diversify the portfolio of tree species that can be used in both commercial forestry and ecosystem restoration during climate change (Grady and Axelsson, 2023).

Lesson Six: *Inclusion of research as an integral part of the project from the beginning to ensure project efficiency and effectiveness.*

We recommend that restoration projects consider research development in their project planning at project onset. Just as in many similar restoration projects, the initial focus in the Sow-A-Seed project was on the operational activities, as few envisioned the project to live after the first five to ten years of funding. Because of this, research components were built into the project at later phases of the project. Throughout the later phases of the project, there were a number of long-term experimental research plots installed that continue to generate information valuable for future restoration projects (Romell et al., 2008; Gustafsson et al., 2016; Axelsson et al., 2020; Axelsson et al., 2021; Axelsson et al., 2022; Cowan et al., 2022; Axelsson et al., 2023; Cowan et al., 2023). However, early studies focused on the planted trees, and it took until the fourth phase before we established random control plots where we could study the ecosystem level recovery of the forest. Setting up research infrastructure in collaboration with local research institutions increases the likelihood of the research plots providing valuable knowledge during and after the restoration phase is over. In connection to the Sow-A-Seed research hub there is also research on forest management within the SUAS (Swedish University of Agricultural Sciences) project (Forshed et al., 2008; Lussetti et al., 2016). A range of Masters and PhD thesis projects both by local students from UMS (Universiti Malaysia Sabah) and foreign students from Sweden, USA, and elsewhere have been conducted in the Sow-A-Seed area and the surroundings. The fourth phase of the project also includes building infrastructure to facilitate future research. This includes species and genetic common gardens with a range of native tree species, and infrastructure for landscape scale studies (see Box 1).

Lesson Seven: *Economic sustainability planning needs to be addressed and implemented before project funds cease.*

Although there may be many benefits from large scale restoration projects for local communities' there are also challenges when projects are coming to an end. Through provision of daily income for many people over a long time and with people also brought in from other regions, we foresee a risk that termination will lead to shortage of employment opportunities. Therefore, we encourage that large-scale restoration projects adopt post-project planning. This may come from planning other sources of income such as in the Sow-A-Seed project building infrastructure for research that can attract research funding and will need research assistance. With the local knowledge built via the project, and with the infrastructure needed for research development, there are opportunities to address important basic and applied ecological questions. Adopting training programs throughout the project may make staff attractive for other employments. Such competence is invaluable not only for the operational activities but also for research development at the site, and for visiting researchers that benefit from guidance and advice from local research assistants.

Although it may not always be possible everywhere due to land tenure issues and conservation needs, other options of continued incomes may come from allowing small scale agroforestry near the restored area. There is an understanding that restoration also provides possibilities for poverty reduction if implemented with consideration for multiple functions and via strong connection to local communities (IPBES, 2018). Agroforestry can be a good source of income in many tropical regions (Mercer, 2004) and is also implemented on restored land across the globe including some sites on Borneo (Normile, 2009). Using the knowledge of native species gained from restoration projects could help in establishment and management of small-scale agroforestry. Such areas could also be implemented as buffer zones to ensure good relationships with local communities and reduce the impact of local communities on interior core areas (Wells and Brandon, 1993; Axelsson and Andersson, 2012).

Lesson eight:*High diversity restoration can create a valuable natural resource.*

Lastly we want to highlight that a key lesson from the work at the Sow-A-Seed project has been that many of the land-use changes occurring directly outside the area (especially forest conversion to oil palm plantations) did not happen within the project area. Engagement in high diversity restoration and research occurring over a period of 25 years clearly contributed to the decision to remove the area from commercial forestry and reclassify the forest area to Class 1 Protected Forest, the highest level of conservation status in Malaysia. The area under conservation included the actively restored area of 14,008 ha but also the untreated forests within the total 18,500 ha and corridors connecting it to other conservation areas. While the forest in the restoration area has not yet reached the complete biomass and structure of undisturbed rainforest, the combination of protection, enrichment planting and assisted natural regeneration has helped the forest to develop faster than would have been possible without the project. Furthermore, to date, all indications from field data show that a range of biodiversity of flora and fauna is supported as a result of 25 years of forest restoration in the Sow-A-Seed area. Camera-trapping and sound recordings indicate that the general species composition is similar to nearby protected forests. Registered species included most of the known wildlife in Sabah, including elephants, the endangered orangutans, banteng, different species of horn-bills and uniquely, all the five wildcats occurring in Sabah (Laneng et al., 2021; Fig. 9). In addition, nine previously undescribed species of follicolous lichens were identified for Sabah from leaves of Dipterocarp species in the INIKEA project area (Shahpuan et al., 2019). The area, that otherwise would have been converted to oil palm plantation, is now a valuable resource for wildlife protection (Fig. 9), eco-tourism, as well as an important infrastructure for research (See Box 1).

4. Conclusions and recommendations

We believe there is much to learn by showcasing experiences learned in operational restoration projects. Sharing knowledge about restoration among practitioners working with the operations and researchers are likely needed in the future (Merritt and Dixon, 2011) to help restoration scale up to meet the growing demand of restoration. Insufficient knowledge has been highlighted as one key hurdle for being able to scale-up restoration to the increasing demand (Gastauer et al., 2020). From our 25 years of experiences working within the Sow-A-Seed project we are providing such knowledge; we now know more about restoration than we did when the project was launched. This knowledge ranges from basic ecology, better understanding of plant propagation techniques, logistics of out planting and costs associated with large-scale restoration projects. We also provide invaluable data on the long-term contribution of tree planting to restoration that typically is lacking in the region (Hector et al., 2011; Banin et al., 2023).

CRediT authorship contribution statement

E. Petter Axelsson: Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kevin C. Grady:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Funding acquisition. **David Alloysius:** Writing – review & editing, Resources, Project administration, Investigation, Data curation. **Jan Falck:** Writing – review & editing, Resources, Project administration, Investigation, Funding acquisition. **Daniel Lussetti:** Writing – review & editing, Investigation. **Charles Santhanaraju Vairappan:** Writing – review & editing, Supervision, Resources, Investigation. **Yap Sau Wai:** Writing – review & editing, Supervision, Resources, Investigation. **Keiko Ioki:** Writing – review & editing, Supervision, Resources, Investigation. **Maria Lourdes T. Lardizabal:** Writing – review & editing, Supervision, Resources, Investigation. **Berhaman Ahmad:** Writing – review & editing, Supervision, Resources, Investigation. **Ulrik Ilstedt:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2024.107282.

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