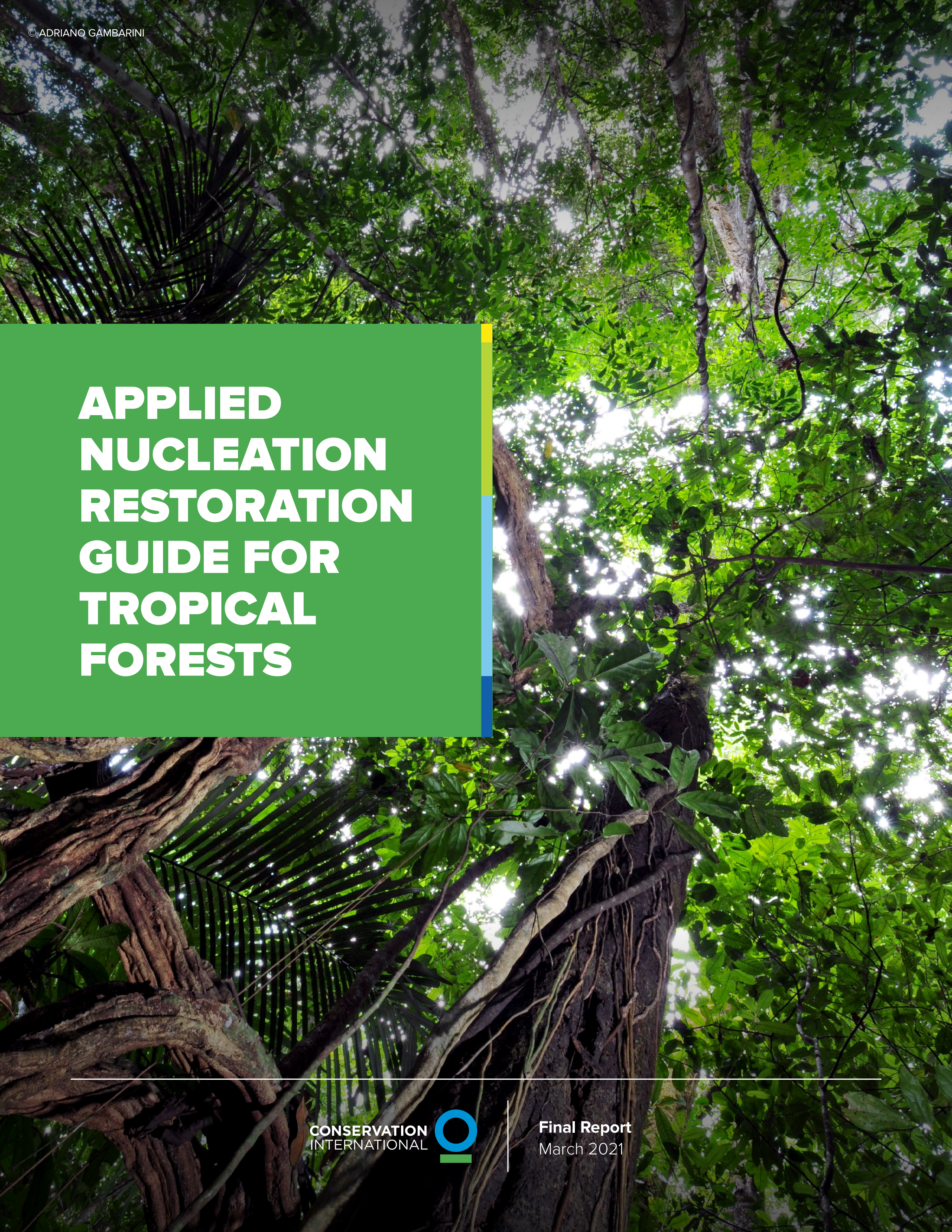

APPLIED NUCLEATION RESTORATION GUIDE FOR TROPICAL FORESTS

CONSERVATION INTERNATIONAL

Final Report
March 2021

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The data presented in this report are the responsibility of the authors and do not necessarily reflect the views of the contractors.

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EXECUTIVE SUMMARY

To meet the global commitments and potential of restoration, innovative and cost-effective solutions are urgently needed. Applied nucleation (AN) is a technique that integrates tree planting and natural succession to restore and regrow forests. Trees are planted in islands, rather than over the whole site, thereby reducing costs and labor. Applied nucleation enhances natural forest recovery and relies on animal species to disperse native trees, which can create forests with high native biodiversity. It holds great potential for restoring forests at scale across the tropics and subtropics

Despite its promise, AN has not been widely implemented. Politicians, donors and practitioners are often not aware of the practice, few large-scale examples have been documented, and to date little guidance exists to implement it. There are also social challenges to its adoption: young recovering habitats, especially those under AN, are often seen as disused or 'wastelands'. Educating both local communities and higher levels of government/policy about the process of AN is critical for success. This guide makes the case for AN, and provides practical guidance for where to use it, design and planning, implementation, and maintaining/monitoring restored sites.

When used in appropriate contexts, applied nucleation:

1. **Is cost effective.** It is cheaper than tree planting, but faster than natural regeneration alone.

2. **Produces comparable results to more intensive planting.** Where ecological conditions permit some natural forest

recovery, AN has been found to be as effective as tree planting over several years.

3. **Is amenable to implementation at scale.** Because of the lower effort required, AN can make tree planting efforts extend farther across the landscape.

4. **Combines the best elements of tree planting and natural regeneration (NR).** Tree planting can provide opportunities for social engagement and integrating locally 'useful' trees, while NR extends tree planting efforts into the landscape.

5. **Is applicable in a wide range of tropical contexts.** Applied nucleation has been used in both tropical and temperate areas, and over a wide range of elevations. There are large areas of the tropics where natural succession could be enhanced, and are thus suitable for AN.

Designing and implementing AN requires a series of steps, including:

1. **Deciding where and when should AN be used** (instead of NR or plantations). Identifying areas suitable for AN, where 1) some recovery is possible but 2) it could be accelerated is a key first step.

2. **Understanding the policy context** and if and how AN can be used as a cost-effective way to restore forests in places where landholders/companies are legally required to restore forests.

3. **Assessing the local needs and experiences with regenerating forests.** Applied nucleation may be less appropriate than traditional plantations in areas where people require direct income from the land.

4. **Deciding where and how trees should be placed on the landscape**, including the size and spacing of islands, in a given context. More, larger islands likely mean faster results, but at higher cost.

5. **Selecting species** that will grow well, expand canopy cover rapidly, and attract seed dispersers to the site.

6. **Planning for maintenance and monitoring**. This generally includes caring for planted seedlings, and managing vegetation, fires, etc. in areas that are naturally regenerating between tree islands.

INTRODUCTION

PURPOSE AND SCOPE

Applied nucleation (AN) is a restoration strategy in which islands of trees (also called nuclei or clusters) are planted to accelerate recovery of forest habitat. Applied nucleation can be a component of 'assisted natural regeneration' (ANR), in which practitioners help accelerate natural forest recovery processes through protecting, managing and/or maintaining regenerating forests (1, 2). Other methods of creating nuclei exist, such as sowing seeds directly in clusters, but this guide focuses exclusively on using trees planted in "islands." The guide covers why, how, when and where to use AN to restore tropical forests, including planning and design elements, logistical considerations, and AN-specific guidance for site maintenance and monitoring. It also provides guidance for learning from practice and includes case examples.

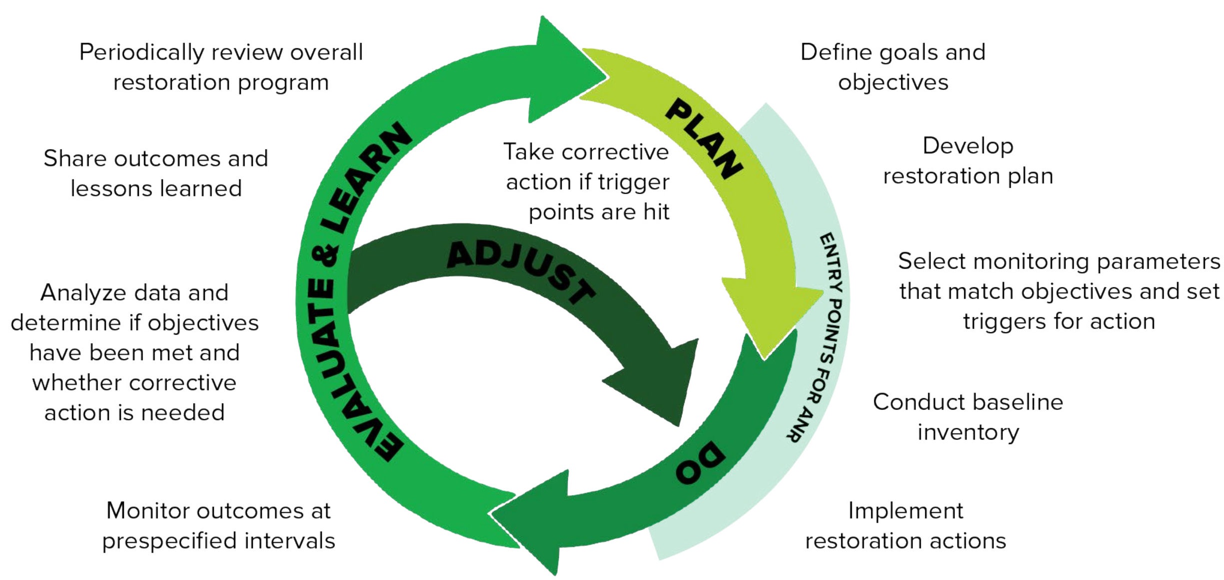

Figure 1. The restoration process based on an adaptive management cycle (modified from (4)). Applied nucleation can be considered as a possible method in planning and implementation stages, depending on project goals, financial resources and ecological site conditions. This guide provides detailed information for integrating AN into the larger restoration process.

Applied nucleation is a technique that should be situated within a wider restoration framework (Figure 1) that includes processes for site selection, engaging stakeholders, setting goals, implementation and monitoring. These critical components of restoration (3) are covered well in section 9: Resources.

THE NEED FOR THIS GUIDE

The United Nations General Assembly declared 2021-2030 the UN Decade on Ecosystem Restoration, with the aim to "massively scale up restoration efforts of degraded and destroyed ecosystems as a proven measure to fight the climate crisis and enhance food security, water supply and biodiversity" (5).

The majority of the world's original forests have been destroyed or degraded (6, 7). Given the critical role that conserving and restoring forests plays in climate change mitigation and adaptation, major tree-planting and forest restoration commitments were launched in the past few years – the Paris Agreement, at least three "Trillion Trees" efforts[1] (8), and the Bonn Challenge all propose to reforest and restore landscapes at vast scales. At the same time, support and publicity for tree-planting efforts is increasing from public, private and corporate sectors.

[1] *1t.org trillion trees effort; Trillion Trees (https://trilliontrees.org/) (join effort between WWF, WCS, and Birdlife International) and Plant for the Planet (https://www.trilliontreecampaign.org/).*

Attention and support for tree planting and restoration are driving commensurate demand for effective implementation techniques. Currently, the resources allocated for restoration are insufficient to meet global targets, and both additional funds and more cost-effective ways of restoring forests are needed (9). Applied nucleation makes tree-planting resources and efforts go farther: it uses tree planting, but at a much lower intensity and cost than traditional methods. Instead of planting trees over the entirety of a site, trees are planted in strategic islands that help forests recover on the rest of the site.

MAKING THE MOST OF THE GLOBAL TREE PLANTING MOVEMENT

Despite unprecedented attention and resources for planting trees, there has not been enough thought as to when, where, and how trees are planted, and how to assess 'success' (10, 11). Most tree-planting efforts focus only on plantation-style tree planting, often without assessing if forests would regenerate naturally without planting, or how much planting is required to aid natural forest recovery (12). Tree planting is essential in some areas where land is heavily degraded or under certain social conditions (Fig. 2). But where forests can grow back, tree planting is also expensive compared to letting forests regenerate naturally and can result in more homogenous forests but could also result in diverse species but ill-adapted to the site, depending on the diversity and successional stage/site requirements of species planted (13). Tree planting also has a bigger ecological footprint than natural regeneration. By planting trees, practitioners predetermine the dominant species for a site for years or decades, sometimes with negative consequences for wildlife habitat or nutrient cycling (14, 15). Inefficiently designed tree-planting efforts represent an ineffective use of limited resources (Box 1). For example, one study showed that in pastures in central Brazil, trees that were regenerating naturally were damaged by tree planting — so planting trees did not increase the number of trees growing overall. In this case, planting seeds of species that did not resprout naturally (rather than seedlings) could have been a better, less labor-intensive option (16).

Tree planting is only one option for restoration, and it works better in some contexts than others (10, 17, 18) (Box 1; Fig. 2). Practitioners, donors and others supporting tree planting should assess and choose restoration strategies based on ecological site conditions (soil, level of degradation, forest type and so on), the amount of forest remaining nearby, land use history, the habitat needs or requirements of key species, and local social and economic needs and goals (17). Where forests can regenerate naturally, protecting regenerating areas may suffice (19). Plantation-style tree planting may be needed where forests are unable to regenerate naturally, where invasive species dominate natural regeneration, and/or where landholders require direct income from the land (18, 20, 21). AN is more appropriate in areas where some natural recovery is possible, but could be accelerated with strategic tree planting (14, 22) (Fig. 2).

Natural Regeneration

In many places, forests may be able to regenerate naturally, and **forest recovery can be achieved by simply protecting these regrowing forests.**

Plantations

Plantation-style tree planting — **where a diversity of native tree species are planted in regularly spaced rows over the entire restoration area** — can be especially effective in degraded areas, and/or areas far from remnant native forests, that are unable or slow to recover unassisted.

Applied Nucleation

Applied nucleation **involves planting strategic islands of trees to accelerate natural forest recovery.** This method is most appropriate in areas where some natural recovery is possible, and can make tree planting efforts go farther in a range of tropical contexts.

Figure 2: Applied nucleation compared other common forest restoration techniques, natural regeneration and plantation-style planting.

BOX 1: GUIDANCE FOR PLANNING AND IMPLEMENTING TREE PLANTING FOR FOREST RESTORATION

Tree planting must be carefully planned and executed, including involving local stakeholders in goal-setting processes; allocating resources to care for and monitor restored sites; and addressing the drivers of forest loss (23). The following guidance can help make tree planting more effective across a range of contexts. See also the 'resources' section for additional tools and guidance.

1. **Identify and take measures to stop the drivers of deforestation.** Effective tree planting requires that practitioners evaluate if forests are still being cleared in the same region, and if so, work to understand the drivers of forest loss and to halt further deforestation. Native and intact forests are higher in biodiversity, store more carbon, and house more rare or endemic species than regenerating forests, and it is nearly impossible to recreate the forest that was there before (24–26) (Fig. 3). Intact forests are also important for restoration efforts, and act as sources of seeds and fauna for nearby regenerating forests (20, 27, 28). Restoration is likely to be faster, and restored forests more species-rich, when remaining forests are protected. An example of how to achieve this (suggested by the Business and Biodiversity Offsets Programme) is to commit that for each area restored, an equivalent area of intact forest must be conserved (29).

2. **Evaluate if planting trees is necessary to meet project goals.** Planners, implementers and donors should carefully consider where, how and whether tree planting is necessary to achieve project goals (10, 12, 30). To decide what restoration strategy is most appropriate, restoration objectives should be clearly stated so planting does not become an objective in itself (10). Too often, metrics like 'number of trees planted' or 'area planted with trees' are used to report the success of a tree-planting project. But for trees to provide carbon sequestration, biodiversity, and other benefits often requires multiple decades. If the ultimate goal is a self-sustaining resilient forest, this goal should guide the planning process and the metrics used to report success. Project goals should be developed in partnership with relevant stakeholders, including local communities and peoples (10, 31, 32). From an ecological perspective, land could be left fallow for a couple of years to see if forests naturally regenerate well and determine if planting is even needed (33).

3. **Understand the land use and landscape context**, including past and current land use, and what is currently on the landscape (including remnant trees and fauna for the seed dispersal component). This will help to determine if tree planting is needed, and if so, how intensively (34).

4. **Seek solutions where tree planting will enhance local production systems and livelihoods**. It is essential to understand how tree planting can fit with local livelihoods and agricultural systems. Without the support of local people, tree-planting efforts often fail due to lack of maintenance and/or protection (35). On the other hand, linking tree planting to sustainable farming practices and implementing it in a way that addresses perceived threats to agriculture can help build support and increase the adoption of these practices widely (31, 36).

5. **Establish a long-term commitment and funding to ensure planted trees survive and grow**. Sustainable financing is critical to achieve successful restoration (10, 37). It starts with acknowledging and planning for the full costs of establishing trees, including 1) the cost of evaluating ecological and social conditions before planting starts, 2) site maintenance after trees are planted (often for 2-5 years, until trees are established) and 3) developing strategies — such as protection against fire and livestock — to ensure the long-term health and persistence of the forest. Often, these essential costs are not considered — for example, many tree-planting programs offer a fixed per-tree price (such as $1 US) that explicitly does not cover the full cost of establishing and maintaining trees. These initiatives decouple

planning and maintenance costs from planting costs and leave practitioners with the difficult task of securing funding for maintaining trees after they have been planted. This has the additive effect of diminishing the perceived cost of tree planting in the market, making it more difficult to obtain funding for effective tree planting

6. **Address the possibility of "leakage", where restoring in one place leads to deforestation elsewhere**. Understanding how reforestation in one place might affect land use in another, for example if it causes the displacement of agriculture or other land use, is important to ensure that the impacts of restoration are "additive".

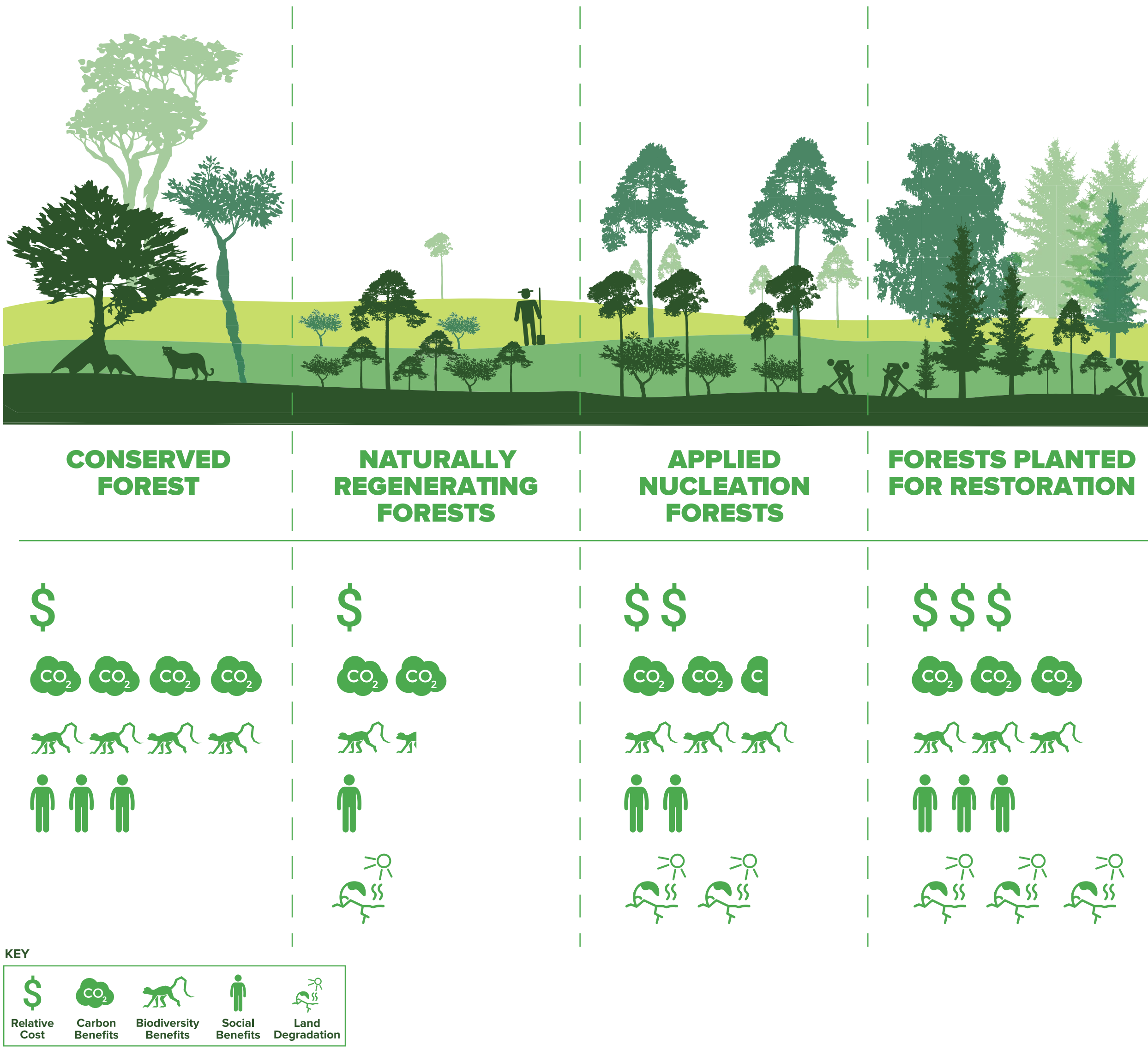

Figure 3: Summary of the costs and benefits of different commonly used restoration techniques over the first 15-20 years (adapted from 2). Note that benefits and costs are context dependent - in some degraded sites natural regeneration is slow or unable to occur and would show far fewer benefits. In this figure it is assumed that the site would be amenable to any of the three restoration techniques. The land degradation metric is suggesting when natural regeneration vs applied nucleation vs plantations interventions should be applied (along a gradient of increasing degradation).

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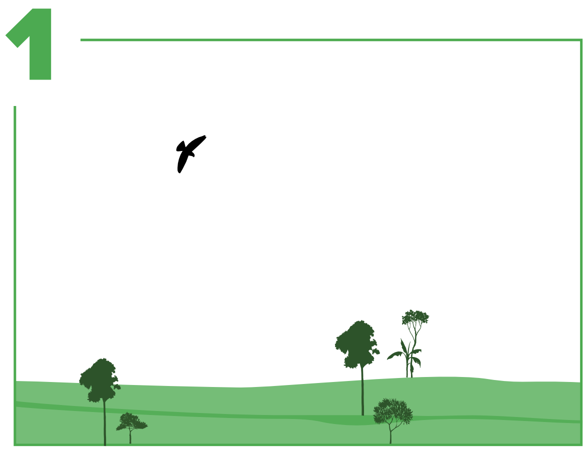
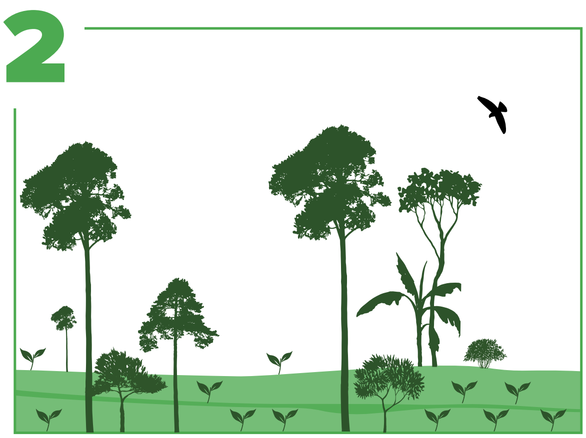
SECTION 1:

APPLIED NUCLEATION: WHAT IS IT, AND WHY USE IT?

WHAT IS APPLIED NUCLEATION, AND HOW DOES IT WORK?

Applied nucleation (AN)— also called 'tree islands' or 'cluster planting' — involves planting small islands of trees that 1) create habitat for seed dispersers, 2) provide shade to suppress the growth of sun-loving plants and other conditions that enhance tree growth, and 3) export seeds from planted trees into the surrounding landscape (Fig. 4). Applied nucleation mimics the natural process of succession, and these attributes help the surrounding area to regenerate more quickly than by natural regeneration alone. Trees can be planted in small islands, or in strips or other configurations (see case study 6), depending on the ecosystem, landscape and project goals (39). Applied nucleation only works if forests can regenerate naturally (e.g., if the abiotic and biotic conditions are suitable) in which case it can facilitate and speed up the process.





After a disturbance, isolated patches of early pioneer tree species start to return. Under their sparse canopies, the climate is cooler and moister than the surrounding area, which creates more favorable conditions for longer-lived species. Canopies attract birds and other key seed-dispersing animals that defecate from the branches, adding to the pool of tree seeds. Over time, these scattered tree canopies act as nurseries, and other trees will germinate and grow underneath and around the edges, expanding the size of the tree patch. Eventually, patches join, closing the canopy and making a continuous forest.

Figure 4: The process of forest succession/natural regeneration happens patchily through the establishment and spread of clusters of trees.

Applied nucleation is based on the nucleation model of succession, a pattern where vegetation recovers in patches following a disturbance such as a fire or windstorm. The first plants to return to the disturbed site modify the environment to make it more favorable for later arrivals, so over time the developing vegetation patches expand and merge together (40) (Fig. 4, Fig. 5). Applied nucleation relies on the forests and trees around the site as seed sources, and speeds up this process by establishing those first tree patches through tree planting. When nearby forest patches are absent, isolated trees in fields or live fences in agricultural landscapes can provide sources of seeds (sometimes even of late successional species), so protecting these trees is also important.

WHY USE APPLIED NUCLEATION?

Where conditions are suitable AN can help restore forests as well as or even better than traditional tree planting does, but at lower cost per area. The effort required compared with traditional tree planting is low: For example, in a long-term AN experiment, plots that were planted with only 27% of the trees used in nearby plantation-style plots showed similar degrees of recovery after 10-15 years (22). The appropriate percentage of land area to plant depends on 1) the resources available and 2) how fast forests can regenerate naturally.

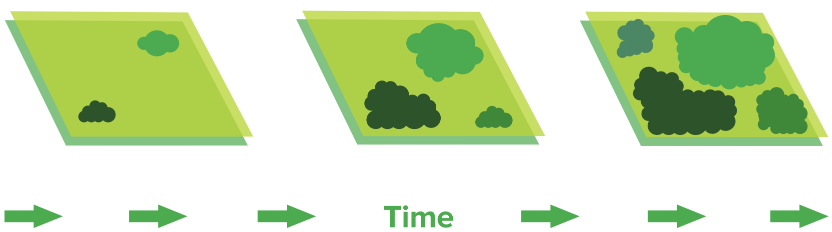


Figure 5: Natural regeneration via the **nucleation model of succession** as seen from above (adapted from (41)). Applied nucleation speeds up this process by establishing those first tree islands through tree planting, as opposed to waiting for them to naturally establish (which may never happen in especially degraded sites). The actual time required for recovery of tree cover will vary greatly depending on site conditions and the spacing and size of the tree islands.

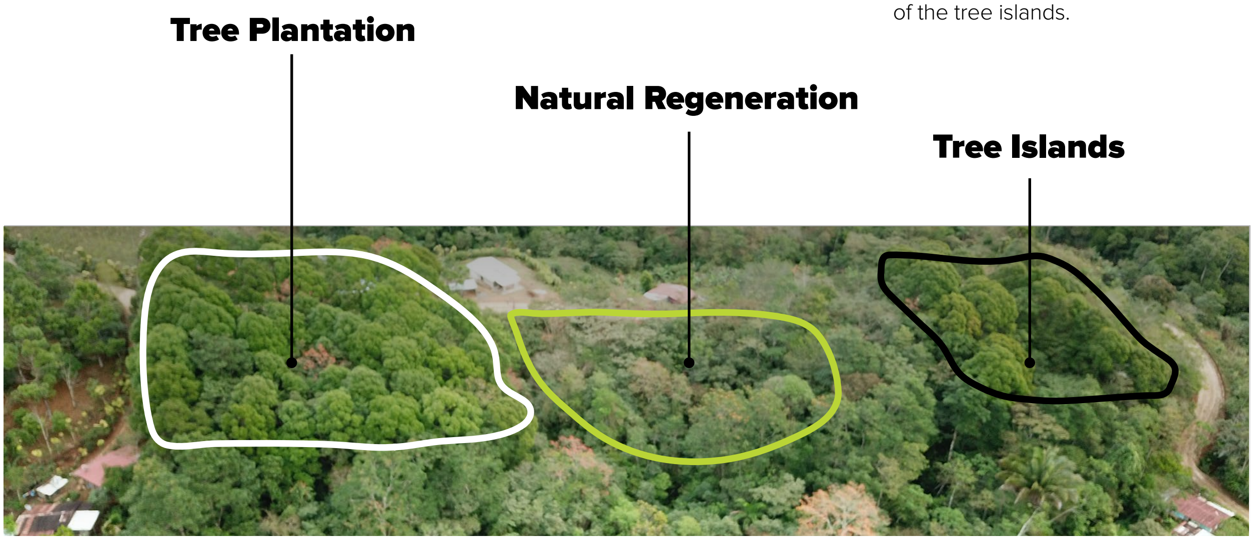


Figure 6: Applied nucleation study sites in Costa Rica after 7-8 years (adapted from (41)).

Applied nucleation has been studied in several ecosystems, including tropical and temperate forests, lowland and premontane/mid-elevation forest, dry shrublands and grasslands (e.g., (22, 42–44). However, only a few studies compared the results of AN to plantation-style tree planting, natural regeneration, and a primary forest reference site, which limits comparison of AN outcomes relative to other methods (22) (Fig. 3, Fig. 6). But these studies show that if used in appropriate conditions, applied nucleation can produce similar canopy closure, tree recruitment (new trees growing at the site), species richness of trees, and seed dispersal processes to plantation-style planting (22, 45). Small-scale experiments suggest AN could be a good option for meeting large-scale forest restoration commitments (22), but larger scale tests of this method are needed.

A
Old fields invaded by *Megathyrsus maximus* before planting tree islands

B
Future tree island cleared of *Megathyrsus maximus* just before planting

C
Maintenance clearing of invasive non-native grasses about 3-6 months after planting

D
25 months after planting. Rows of *Heliocarpus americanus* trees are visible

Figure 7: The results of AN in the field after only two years regrowth in premontane forest, Columbia (case example 3).

COST

AN is less expensive than traditional tree-planting methods (46). In AN, many costs are scaled to the area planted, which means that an AN area planted with 20% the number of trees would cost a fifth of what a plantation would (47-49). Fixed costs, such as protecting forests, monitoring, compensating landholders, land costs, project planning and so forth, would remain similar for AN, tree planting, and natural regeneration, and should be estimated separately to calculate the overall cost (Fig. 8). While comparisons vary, AN is generally cost-effective and can make tree planting investments stretch farther, provided it is used in appropriate social and ecological conditions.

Cost Category	NR	AN	Planting	Notes
Community engagement, planning and education	$	$	$	AN and NR may require more explanation because they are less familiar.
Land	$	$	$	There may be slightly higher costs for AN and NR if they are not seen to offer the benefits of tree planting.
Monitoring	$	$	$	
Plant materials	–	$	$ $ $	Depends on density of trees planted for AN.
Planting labour	–	$	$ $ $	Depends on density of trees planted for AN.
Maintenance - weeding around planted trees	–	$	$ $	May be more labour intensive to clear around patches of trees not planted in rows; non-forest plants may take longer to be shaded out.
Grazer exclusion	$ $	$ $	$	May be higher for NR and AN because pasture grass persists longer.
Fire protection	$ $	$ $	$	May be higher for NR and AN because vegetation between islands is more flammable.
Illegal land use/ harvesting	$ $	$ $	$	May be higher for NR and AN because trees confer ownership/demonstrate use; people may graze livestock on grass. When planted trees are larger, this may reverse as people harvest planted trees.

Figure 8: Relative costs of applied nucleation (AN) as compared to traditional plantation-style planting (Planting) and natural regeneration (NR). Note that 'fixed' costs per unit area do not vary with the area restored, while 'scalable' do. (Adapted from (50)). Costs are relative along each row, but not by column.

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SECTION 2:

SOCIAL AND CULTURAL CHALLENGES AND OPPORTUNITIES FOR APPLIED NUCLEATION.

Applied nucleation is still not widely used or recognized as a restoration technique, as such its implementation can present cultural, legal and political challenges. Aligning the goals of restoration with the needs of local people through stakeholder engagement and participatory planning design is key to ensure restoration is accepted, protected and persists over time. Understanding who uses the land and how; the impact of national policies on local land use; goal-setting; and considering how AN can fit into a working landscape are all critical. A full discussion on stakeholder engagement is beyond the scope of this guide, but there are many resources available (see end of section).

Many people expect restoration to be orderly and to see rapid results. Planting trees in rows matches those expectations if the trees survive and grow well. On the other hand, naturally regenerating areas usually take time to grow into something that looks like a "forest" (51). Early on, these areas are sometimes considered unused or barren, and may risk being reclaimed or used for non-forest purposes (22, 52). In AN, areas between tree islands undergoing natural regeneration are often perceived as "messy" — scrubbier and less orderly, which may not align with cultural norms and preferences (22, 51). Young regenerating forests may also not be considered "forest" under policy or by local landholders until they reach a certain size, cover a certain area, or until key species return (Wilson, unpublished data) (11, 53). Until these criteria are met, regenerating vegetation is at greater risk of being cleared (54, 55). Allowing forests to regenerate naturally also requires little action on the part of landholders aside from protecting the land, which is very different from the investment required and orderliness of farming or plantation-style tree planting and can represent a major shift in thinking about land use and management (36, 56, 57). Therefore, it may be necessary to provide additional outreach to landholders in the early stages of implementation, to help them see the important process happening inside the "mess." Demonstration sites where people can see how effective AN can be firsthand are helpful for educating local landholders about the technique (56) (Case study 4 this guide).

Applied nucleation can make use of the active tree planting component to overcome some of the challenges faced by natural regeneration. Tree planting makes restoration more appealing to landowners because:

1. It is hands-on, active, requires work and investment, and gives landholders some control over the outcomes.
2. It shows land is being used, which can reduce intrusions, and in some contexts indicates ownership (formally or informally). For example, in the Philippines planting trees can confer both informal and formal rights to land through the Certificate of Tree Plantation Ownership once areas have been planted with trees.
3. It can be used to establish beneficial species.
4. It is recognized by many governments and agencies as the primary way to restore forests.

To make the best use of tree planting in AN, practitioners should engage local landholders and other stakeholders to design the AN area; and work to understand policies (past and current) on land claims through use. Some example solutions are:

Figure 9: Members of the local community processing seeds and selecting high-quality, healthy seed specimens for restoration of a locally threatened species in Colombia (Photos by Angélica Cogollo) (Case example 3).

Figure 10: Social challenges and opportunities posed by applied nucleation as a restoration technique, and possible ways to overcome them. (a) often restoration is seen to be messy, or land is considered unused or barren in the early stages of regeneration. Potential possible solutions are: b) planting trees along property lines; c) planting locally useful species in islands for harvest; d) using tree planting to engage communities and stakeholders.

2. Practitioners could consider how to demonstrate that land is being used in the planting design by altering the configuration of the plantings to, for example, define property lines or otherwise demonstrate intentionality.

3. Locally valued species could be planted in tree islands, and in regenerating areas — planting marketable species has been found to increase community support and increase a sense of ownership in naturally regenerating areas (57, 58).

4. Tree planting can be used to engage communities and provide local employment to increase support for restoration.

The case studies presented in this guide provide examples of how AN intentionally engaged marginalized communities to do the work, including training and capacity building, and the positive social impact that this had (Case examples 2 and 4) (Fig. 9). AN, like other active restoration activities, can become an opportunity to provide meaningful employment and build community, with thoughtful and inclusive planning (Fig. 10).

TOOLS AND RESOURCES

For the general process of understanding local use and engaging stakeholders:

- A Guide to the Restoration Opportunities Assessment Methodology (ROAM): Assessing forest landscape restoration opportunities at the national or sub-national Level. *IUCN: International Union for Conservation of Nature & WRI: World Resources Institute*, 2014. (see pages 58 to 63 for the Stakeholder Prioritization of Restoration Interventions tool and other relevant information).

- Land Use Dialogue Guide: Dialogue as a tool for landscape approaches to environmental challenges. *TFD: The Forests Dialogue*, 2020. (for more information, visit https://theforestsdialogue.org/initiative/land-use-dialogues-luds).

- Peace Corps Participatory Analysis for Community Action (PACA) Training Manual. *Peace Corp*, 2007. (Oriented towards use at the community level).

- Good Practices in Participatory Mapping: A review prepared for the International Fund for Agricultural Development (IFAD). *IFAD*, 2009.

- Rapid Rural Appraisal and Participatory Rural Appraisal: A manual for CRS field workers and partners. Freudenberger, K. S., *CRS: Catholic Relief Services*, 2008.

For choosing species:

- Agroforestry Tree Domestication: A primer. Dawson et al., *ICRAF: The World Agroforestry Centre*, 2012

- In Equal Measure: A user guide to gender analysis in agroforestry. Catacutan et al. (Eds), *ICRAF: The World Agroforestry Centre*, 2014.

For understanding how to make ANR more relevant to local land users:

- Assisted Natural Regeneration: Methods, results and issues relevant to sustained participation by communities. Dugan, P. In Forest Restoration for Wildlife Conservation. Elliott, et al. (Eds), *ITTO: International Tropical Timber Organisation & FORRU: The Forest Restoration Research Unit*, 2000.

BOX 2: USING APPLIED NUCLEATION AT LARGER SCALES

Applied nucleation has good potential for restoring forests at scale, with less cost and effort than traditional tree planting within comparable timeframes (22). Only a few examples exist to date where AN has been implemented at larger scales, including the Osa Peninsula in Costa Rica (Osa Conservation) and in Madagascar (Green Again Madagascar, Case Study 5) (22), and outcomes have not yet been published. Studies of AN at larger scales (e.g., 1,000 to 5,000 ha) would be very valuable to inform future efforts.

In the absence of field data, practical guidance for adapting AN to larger scales includes:

1. **Within a larger area (like a landscape) determine what areas are most suitable for AN, and where other techniques might be more appropriate**. See section 4, below.
2. **AN could be strategically located/combined with other forms of restoration to meet different social goals and legal requirements for restoration**. Using this technique in some areas and more intensive and/or livelihood-oriented restoration in others could help to build support for restoration generally. For example, using AN to restore watershed areas, and woodlots/plantations/agroforestry systems in and around working farmland.
3. **The configuration and/or size of tree islands may be modified over larger areas**, depending on the project goals, timelines, site conditions, species choice, and forest type. (See section 6 below).

Example of an AN project implemented in 2019 by Laura Toro and Fundacion Natura. 42 hexagons were established in a 7 ha grassland previously used for agriculture and grazing for 50+ years. Hexagons measured 35 m across and were spaced 15 m apart. Within each 271 individual trees 11 species were planted, spaced 1 m apart. Photos were taken during and shortly after planting. *Photo credit: Fundacion Natura and Laura Toro.*

A

B

C

SECTION 3:

WHEN AND WHERE SHOULD APPLIED NUCLEATION BE USED (VS. OTHER TECHNIQUES)?

Applied nucleation is most effective where forests can regenerate naturally to some extent, but regeneration is slow (Fig. 2, Fig. 11). Past land use, proximity to existing forests or lone trees, and the size of the patches of remnant forest all affect regeneration and thus the potential for AN (17, 21, 59, 60). Applied nucleation works by creating 1) areas where seed dispersers can find refuge and travel from one island to the next, and 2) favorable conditions for seeds to establish (14) (Fig. 3). Areas lacking these nuclei (remnant trees or patches) could particularly benefit from AN (22).

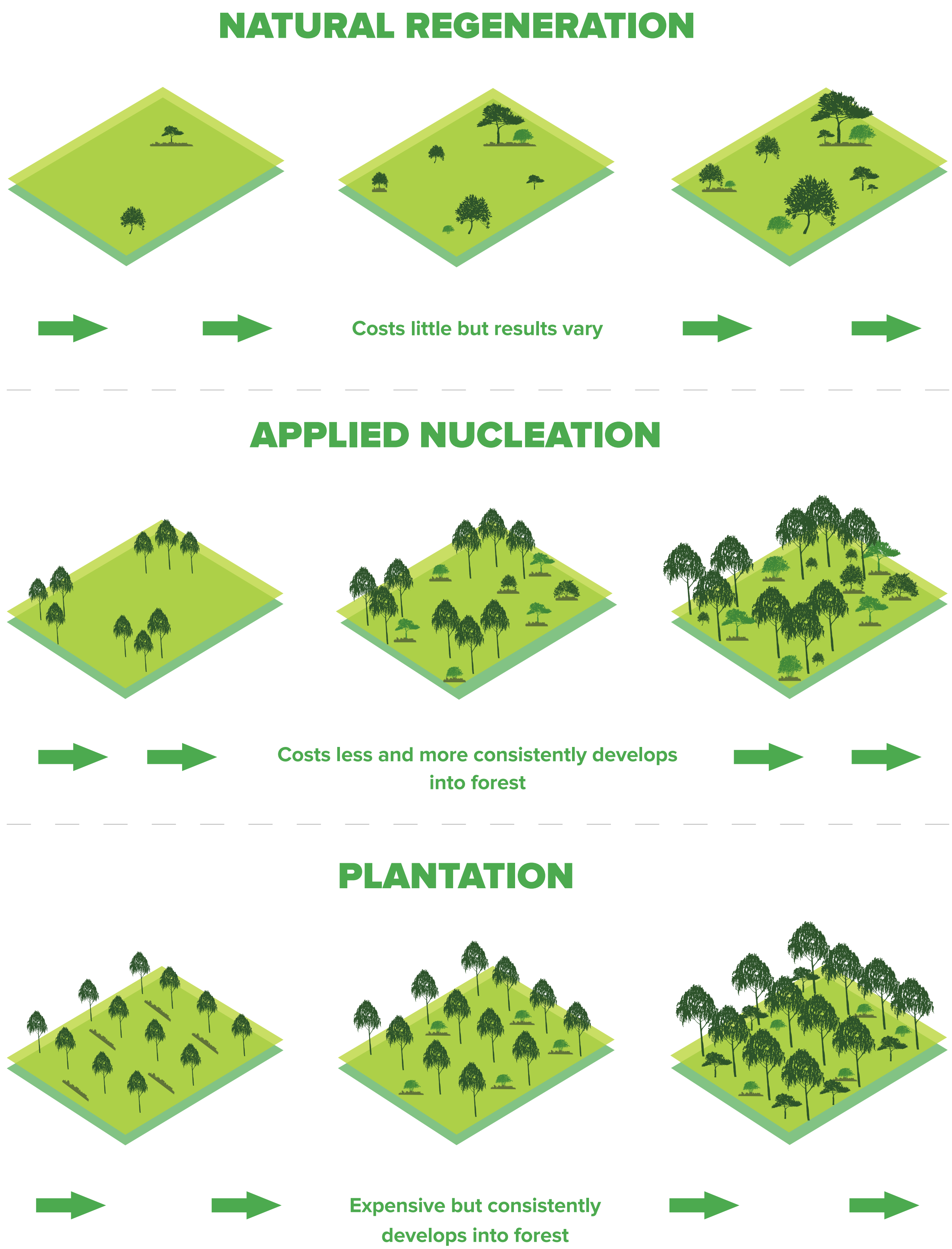

Figure 11: The process and outcomes of natural regeneration, applied nucleation, and plantation-style planting over time (adapted from (14)). For the sake of simplicity, only one tree type is illustrated as being planted, and all the other species colonize naturally. In reality, both tree nuclei and plantations would ideally include multiple species.

Sites far from forests where land is more degraded/slow to recover naturally may require more intensive tree planting, while in areas where forests can regenerate well unassisted, natural regeneration may be sufficient for forest recovery (Fig. 11). This section provides guidance for assessing if applied nucleation might be a good fit based on local site conditions (Fig. 13).

1. **Applied nucleation is compatible with the needs and goals of local landholders**. AN can be a good option where restoration goals aim to restore native forest cover, and for watershed or soil protection. Where landholders require income/food harvests from reforested areas, more intense planting of valuable trees and/or installing agroforestry systems may be better options. Or, these systems could be combined with AN at the landscape scale. Enrichment planting in AN or NR areas can also be used to integrate valuable species.

2. **Regenerating forests are valued/ culturally accepted**. Regenerating forest areas are often seen as unclaimed or unused, which can lead to problems with use rights and tenure claims (52) (see section 2, above). Applied nucleation may be a better choice where it is culturally more likely to be accepted, or if not, where the resources and potential exist for training or demonstration sites,

	Recommended strategies in given conditions		
Site Conditions	**NR**	**AN**	**Plantations**
Forest species recovery when land is left fallow for 1-2 years	Fast recovery	Some recovery but slow/ impeded	Little/no recovery
Presence of seed dispersers	Present/likely present	Present/ likely present	Not present/ very few
Sources of seeds (remnant forests, pasture trees) present on the landscape	Trees and/or remnant forest nearby	Trees and/or remnant forest nearby	Few to no remnant forests or trees present
Presence of tree-suppressing species, e.g., competitive, sun-loving species like pasture grass	Few/less dense	Abundant to moderate	Abundant to moderate
Past land use; burning cycles.	Moderate to lightly used sites, no burning/ long fire cycles	Moderately used sites; some burning okay	Heavily used sites with repeated burning
	Project goals and other considerations		
Provide income to landholders	Income generation not essential	Income generation a secondary goal/ not essential	Income generation important
Compatibility with other landholder goals	Restore native forest cover	Restore native forest cover, watershed or soil protection. Potential for valuable species to be planted in smaller amounts	Harvests of food or timber possible through plantations or agroforestry systems
Area to be planted, funding available	Funds per unit area minimal	Funds per unit area limited	Relatively high funding per area to be restored

Figure 12: When to use AN versus other common techniques based on site conditions and project goals.

education and/or policy change. Dialogue with local organizations is necessary to understand how landholders view and use regenerating forest. Large protected areas with limited funding and where local people do not need to make money from the land could be especially good candidates (for example, degraded land that was recently added to a reserve or national park; and/or where funding to restore large areas is limited (22)). See section 2, above, for tools and guidance for understanding livelihoods and land use and landholder needs, goals, and perceptions.

3. **Forest recovery is able to occur, but is generally slow or delayed**. If the site already has lots of native tree seedlings, this is a good indication that natural regeneration can occur. But if not, consider running the following:

   A. **Test natural regeneration potential by allowing the land to recover for 1.5 to 2 years.** The amount of recovery after 1.5 years is a good predictor of future recovery (33). If forest species start to return after a 1-2 year fallow period the site may be a good candidate for NR or AN.

      i. **To evaluate if a site is recovering well, the % grass cover, % canopy cover, and tree seedling density should be measured.** For example, canopy cover of >10% and grass cover of < 70% after 1.5 years was associated with higher recovery eight years later in Costa Rica. Other systems may have different proportions, and the type of grass also has an impact. For additional guidance, see (33) (and also the section below on 'site treatment').

   B. **When it is not possible to wait 1-2 years, consider the intensity of past land use and the surrounding landscape to assess regeneration potential.**

      i. **Intensity of past land use:** Areas that have been cleared for longer periods; have been repeatedly cleared; where soils are degraded/eroded; and where fire has been used repeatedly to clear forests are less likely to recover naturally, less likely to have a robust seed bank, and may require more intensive methods.

      - *History of repeated fire: Has the land been repeatedly burned (e.g., over several fallow cycles?) → if so, forest recovery may be impeded due to a lack of seed bank and other propagules (61-63). Frequent wildfires may also make a site difficult to restore with AN, because vegetation between islands may be highly flammable (more so than forests) (64).*
      - *Poor soil conditions: Have soils been severely eroded or compacted? → if so, natural seedling establishment will be very limited until soils recover, and plantation-style tree planting of species that are tolerant of such soils, N-fixers, and/or soil enrichment with compost prior to planting may be required for effective restoration.*
      - *Long time since clearing: When was the site cleared? → Longer durations of anthropogenic land use are often associated with poorer recovery (61) since soils become less fertile with ongoing use and the seed bank diminishes over time.*
      - *Invasive species: Highly invasive shade-tolerant species (especially invasive trees) on the site could mean applied nucleation will not work, especially if they fill in all of the interstitial space between islands (14). Dominance of invasive species (e.g., in Hawaii) may prevent AN expansion and limit effectiveness.*

ii. **Remnant forests/trees are present in the agricultural landscape.** Remnant forest can serve as important seed sources, and habitat for seed dispersers, as can remnant trees interspersed in the agricultural landscape.

iii. **Seed dispersers are present and are able to use islands.** Having abundant seed dispersers at a site is favorable for AN. But seed dispersers are not always easy to observe, so this step should not be used to rule out AN.

- *Tools and guidance for assessing seed disperser presence: the presence of seed dispersers can be assessed quickly in the field through direct observation of wildlife visitation at sites, including counts (point counts or timed area counts) and camera traps. Wildlife observations do not require much assistance, but do require knowledge of potential disperser species - engaging with local communities and naturalists would be helpful. To interpret results of wildlife observations:*
    - If smaller, omnivorous or frugivorous birds are present, it is likely that small-seeded pioneer species are being dispersed. (Places where you would not expect to see these include vast monocrop plantations, or islands where they are largely absent (like the island of Guam, e.g., (65)).
    - If large frugivorous birds (e.g., toucans, hornbills) or mammals (e.g., monkeys, lemurs, flying foxes) are present, they can serve to disperse larger-seeded plant species found in the area (66, 67).
    - Note that some seed-dispersing animals can be inconspicuous, such as leaf-nosed bats (68).

4. **The surrounding vegetation is predominantly native species**. Because the regenerating forest relies on seeds dispersed from nearby trees, the quality of the nearby forest or trees matters too. Although forest cover can increase with a range of different levels of forest/tree cover, the species composition of regenerating forest is strongly affected by existing forest in the landscape (Zahawi, unpublished data/in progress). Applied nucleation is a poor strategy in places where the seeds being dispersed are primarily from invasive species.

5. **Other stressors - herbivory, wildfire, and so on - that could destroy regenerating vegetation are able to be managed.** Secondary regrowth is often cleared within years to decades of starting to regenerate (55, 69). For applied nucleation or any forest restoration strategy to be effective, threats to regenerating forest (especially when young) need to be managed/ removed (17).

TOOLS AND RESOURCES

- Rules of Thumb for Predicting Tropical Forest Recovery. Holl et al., *Applied Vegetation Science*, 21(4), 2018.
- See also the tools and resources on stakeholder engagement from section 2.


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SECTION 4:

TREE ISLAND SIZE, SHAPE, SPACING AND CONFIGURATION

ISLAND SIZE AND SPACING

For a given planting effort, should practitioners plant fewer, larger islands, or more smaller islands? There are tradeoffs between island size and distance between islands for the same planting effort. Larger, closer islands tend to perform better and increase recovery speed up to a point, but island size and spacing between islands also depends on project goals, timelines, and budget. Results from Costa Rica and Honduras where islands were separated by ~8-20 m (CR) and 12 m (Honduras) both show good results, but recovery was slower when nuclei were spaced at greater distances. Given that few studies directly assess optimal distance between islands, a default spacing may be 8-12 m based on prior studies but further experiments are warranted.

WHAT IS THE OPTIMAL TREE ISLAND SIZE?

Tree islands should be large enough to attract birds and other seed dispersers (70) and shade out pasture grasses. The optimal size depends on the local context and forest type. In Costa Rica and Honduras, smaller islands (28 and 50 m2) tended to have more grass in the understory (45, 59), and were more affected by the death of even one planted tree (especially the center one, which leaves little island core remaining). Larger islands (64 and 144 m2 planted area) had more bird visits, more animal-dispersed seeds, and facilitated more tree recruitment than smaller islands (22, 59, 60, 70, 71), so a minimum size of 64m2 was recommended (22, 59). However, the cases presented at the end of this guide demonstrated that AN still increased forest recovery over natural regeneration using circular islands of only 2-m diameter (3.14m2) in Brazil (case study 4) and 6-m diameter (28.3 m2) in upper montane cloud forest in Colombia (case study 3) (in both cases, trees were very densely planted within islands, 0.5 and 1.1 m apart respectively). Additional research is required to determine the minimum size in other forest types, like tropical dry forest.

Ultimately, above a minimum threshold the maximum size of the island **depends largely on the project resources, forest type and the total area to be restored**. Larger islands cover more ground, and may provide slightly better habitat — but also require more resources. Balancing total area covered, spacing between islands, and the size of each island is a key consideration.

HOW MUCH AREA SHOULD BE PLANTED, AND HOW SHOULD ISLANDS BE SPACED? CONSIDER THESE FACTORS:

1. **Assess the degree of disturbance/ degradation at the site**. More disturbed, degraded sites will require more intensive tree planting, which could mean spacing islands closer together.
2. **Estimate the growth rate of canopy**. Islands planted with trees that develop wide canopies quickly may mean that islands might be spaced farther; slower growth, closer.
3. **Consider the resources available for tree planting**. Planting a larger percentage of a restoration site with islands will most likely result in faster recovery, but more tree planting increases project cost. At a certain point, the relative advantage of AN over traditional tree planting will be lost if tree planting becomes too intensive.

WHICH SHAPE OF ISLAND IS MOST SUITABLE IN A GIVEN CONTEXT?

Squares or circles are most commonly used (Fig. 13). Circles produce the best edge to inner forest ratio, but the edges may be harder to locate and maintain (e.g., planted seedlings might be mistakenly cleared). Other shapes can also be used so long as they create shaded habitat within islands. For example, strips are easier to plant and maintain because there are fewer corner positions to locate in dense secondary vegetation, and many traditional forestry practices use this configuration. In Brazil, trees were planted in strips, and observations after three years suggest that forest recovery is similar in areas planted with islands and strips, but that strips were much easier to install (case example 6).

HOW CLOSELY SHOULD TREES BE PLANTED WITHIN ISLANDS?

The answer depends largely on project goals, available resources, and the growth rates of species used (72, 73). Traditional-style tree planting for restoration has shown good results using a wide range of spacing (often 1 to 4m). A study testing natural regeneration under planted trees found that more closely spaced planted trees (2x2 m) led to a greater diversity of regenerating seedlings than more widely

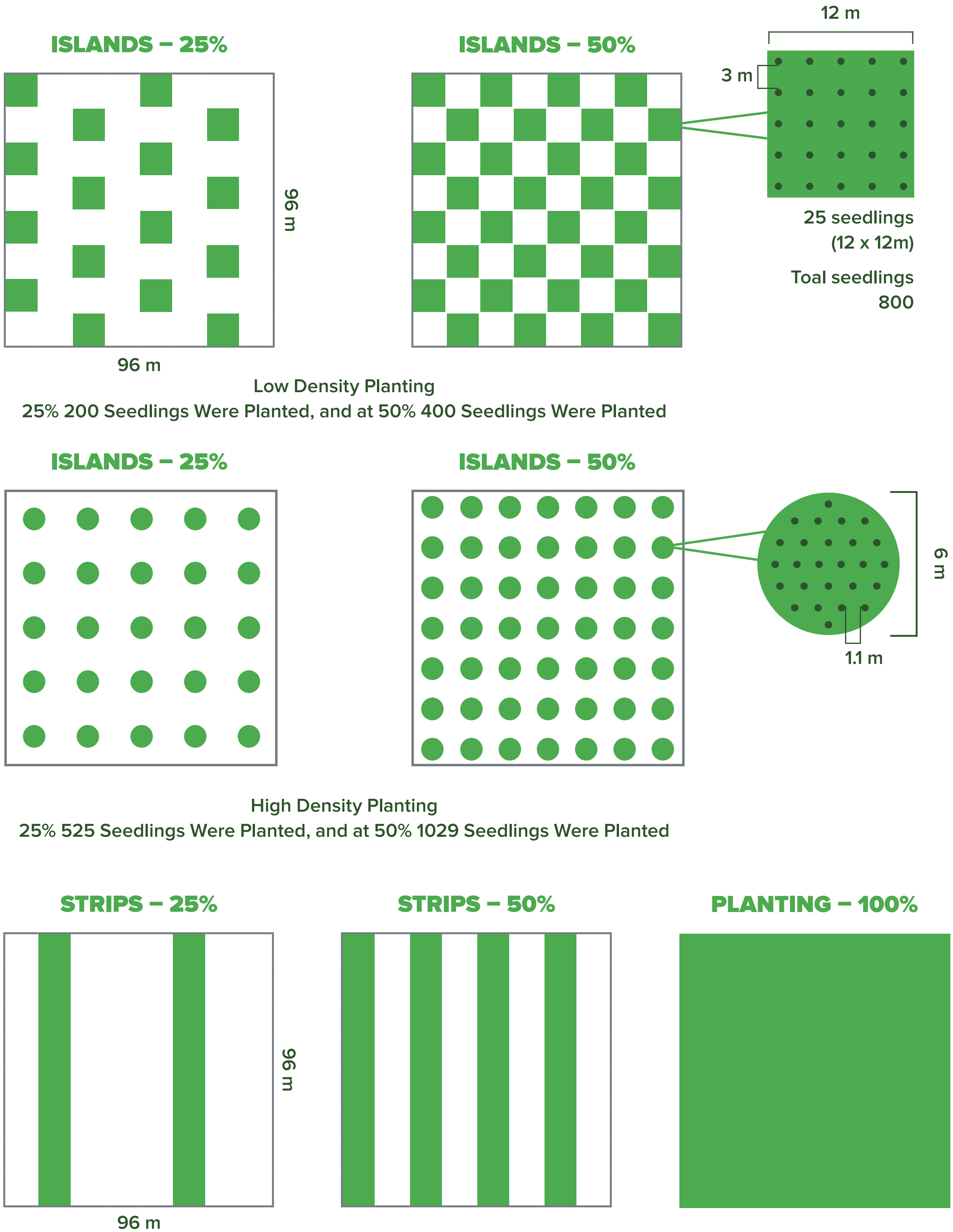

Figure 13: Examples of alternative designs for applied nucleation. Note that in this figure squares provide an example of 'low density' planting (trees spaced farther apart within each island) and circles an example of 'high density' planting. Squares, circles and strips are all represented in the case examples in this guide (squares cases 1 and 5; circles cases 2, 3 and 4; and both squares and strips in case 6).

spaced trees (3x3m) but the abundance of individuals was similar (74). Mixed plantations at 3x3m spacing to restore native vegetation in the Brazilian Savanna were found to be successful in terms of growth, especially for biomass accumulation and carbon stock.

The advantages of wider spacing (> 2m, typically 3m) are that it 1) uses fewer project resources as fewer trees are planted in each island, 2) can promote taller tree growth, a good attribute if some trees will eventually be harvested; and 3) produces trees with a wider trunk diameter (75–77). Closer spacings (less than 2m) are used to encourage forest competition and diversity (73). This practice is also used in urban micro forests to create dense, multi-layered strata (78). Advantages of closer spacing include 1) closing the canopy within islands more quickly; 2) potentially creating more 'natural' forest conditions from the start; 3) producing more biomass more quickly (1.5-2m) (79, 80); and 4) reducing available space for invasive species.

One of the main advantages of AN over traditional tree planting is that it uses fewer resources. Because the number of trees in islands is the squared distance between trees, the total number of trees needed goes up quickly when spacing is reduced. In Madagascar and Colombia good results were obtained with 1-m spacing, and in Madagascar, trials are underway to test 'cheap' (low density planting) vs. 'dense' (higher density planting) islands (Case study 5). A case in Colombia explicitly tested planting density (0.9 vs. 1.1 m) and found faster tree growth at less dense spacing, which also reduced project expenditure by about 30% (Case study 2). In Brazil, planting trees 0.5 m apart in small islands also produced good results (Case study 4), and in Costa Rica good results were also obtained using trees spaced 3 m apart (Case study 1). Faster growing species with larger canopies mean that forests may become more dense more quickly, making farther spacing appropriate.

A
Aerial view of the plantings.

B
Drone shot of the rows of *Eucalypts* interplanted with rows of native species

C
Planted native tree species after Eucalypts have been harvested for livelihood benefits. The anticipation is that native species will regenerate naturally in the logged area

An example of scaling up strip plantings of mixed native species and Eucalypts over 77ha in Brazil, planted in rows to facilitate planting, maintenance and harvesting. Photo credit Pedro Brancalion. See also case example 6.

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WORKING WITH LANDSCAPE FEATURES

For a given planting effort (e.g., 20%) where on the landscape should trees be planted? Trees can be strategically planted to offer multiple benefits within the landscape. Some general considerations include:

1. **Plant islands in areas where there is less natural regeneration**. Allocating greater planting effort in the more degraded areas 1) targets places where natural regeneration is less likely to occur and 2) establishes tree islands that can accelerate natural regeneration on the rest of the site.

2. **Plant islands in areas that buffer important resources**. For example, favoring islands along riparian areas to minimize erosion, or along a property boundary to make land use appear more intentional (see section 2).

3. **Plant islands to create connectivity** (i.e., between two forest fragments) to enhance landscape processes.

4. **Choose species placement based on landscape context**. For example, if there is a windier part of the parcel and species planted are wind-dispersed, plant them there (81). If a species is water-dispersed, place closest to water, or if reliant on fauna dispersers, plant where scat or other signs of dispersers are present.

GOOD TREE PLANTING PRACTICES ARE ESSENTIAL FOR GOOD OUTCOMES (10, 23)

Applied nucleation plots require effective tree planting techniques to increase survival and growth, including timing the planting with local rainfall cycles to avoid costly irrigation. Tree planting best practices are outside the scope of these guidelines, but there are many resources available including:

- Restoring Tropical Forests: A practical guide. Elliott et al., *Royal Botanic Gardens, Kew*, 2013.

- Implementing Forest Landscape Restoration: A practitioner's guide. Stanturf et al., *IUFRO: International Union of Forest Research Organizations*, 2017.

- Guidelines for the Restoration, Management and Rehabilitation of Degraded and Secondary Tropical Forests. *ITTO: International Tropical Timber Organisation, 2002.*

SECTION 5:

SELECTING SPECIES AND PLANT MATERIALS

Few studies compare species choice across different treatments. This section provides pragmatic principles based on field experience for selecting tree and other plant species (Fig. 14). All species selected should be suitable for the site conditions, including altitude range, precipitation, seasonality, soil type and aspect, over which the restoration will take place.

ECOLOGICAL CONSIDERATIONS

1. **Choose combinations of species that include:**

   A. **At least one fast-growing species** able to establish in the open, with a spreading canopy (spreading via branching is an important way that AN closes the canopy). Species that grow fast and then die (e.g. Inga edulis in case example 1), leaving room for mid-late successional species, are especially useful (22). Garibello (case example 3) also found that in lower montane forest in Colombia, nuclei planted with either Heliocarpus americanus or Fabaceae trees (Inga marginata, Inga sp. and Erythrina poeppigiana) were more effective at facilitating survival of endangered trees, compared to nuclei formed by treelets that commonly colonize old fields (Miconia sp., Piper aduncum, Vismia baccifera).

   B. **A few medium and slow growing species** (mid-successional), particularly species that are unlikely to colonize sites on their own, such as gravity-dispersed species or species with large, animal-dispersed seeds. Later-successional, large-seeded species tend to be absent or slow to return to restored plots without additional assistance (22, 46, 82, 83). These can also be introduced via enrichment planting in the maintenance phase of the project (Section 7, below).

   C. When the above criteria have been met, consider also choosing species that:

      i. Are easy to produce in local nurseries and/or grow well from cuttings (nursery stock can be a serious limiting factor in tropical restoration projects);

      ii. Have a high renewal rate: the parts (leaves, twigs, branches and roots, etc.) are frequently shed and regrown, which creates organic matter and improves soils.

      iii. Have a high capacity to sprout quickly and repeatedly after physical damage (partial felling and/or burning).

2. **Include fruiting trees for animal-dispersed species**: Planted trees attract animals by providing food, shelter from predators, nesting areas, and shade (84). Fruiting trees may increase fauna visitation, seed dispersal, and seedling recruitment compared to wind-dispersed trees (85). Trees with fruits eaten by a large variety of seed dispersing animals may attract more dispersers (86). Figs (Ficus spp.) are recommended for plantings where they are native because they are widespread and their fruits are eaten by a wide array of animals (87–89).

3. **Use native species when possible, and avoid choosing species that will compete with native tree species and prevent their establishment**. Select native species when possible as these species will likely remain in the ecosystem, and avoid especially competitive or tree-suppressing species (22, 90). For example, teak plantations in Costa Rican pastures were found to suppress tree growth as compared to natural regeneration without planted trees (91).

4. **Include nitrogen-fixing species in sites where soil infertility limits native tree regeneration**. Multiple studies have found good results using nitrogen-fixing trees, which often grow quickly and increase nitrogen availability (e.g., Fabaceae family;

Inga spp. and Erythrina poeppigiana) (92) (case example 3).

5. **Consider "Fire-resistant" islands designs in areas prone to frequent fires (in addition to firebreaks)**. Theoretically, fire-resistant trees planted on the border may be able to protect more fire sensitive species in the interior. The species to use, and dimensions of 'fire resistant layers' required, will be highly context-dependent, and there is not yet conclusive experimental evidence to prove this. It is an important area for continued research (see case example 5).

6. **Select non-tree species as appropriate in different contexts**. Shrubs could be suitable species to add to an AN species mix alongside trees, and herbs might also be important to bring back a full species complement in some contexts.

SOCIAL AND ECONOMIC CONSIDERATIONS

7. **Integrate Indigenous and local knowledge and engage local people in the process of species selection**. Local people may be able to identify species that meet both social and ecological goals/criteria for AN, especially in places with a history of forest use/agroforestry systems (93). Local people were involved in species selection in a number of the cases presented in this guide (case examples 2, 3, 4 and 5, in Brazil, Colombia, and Madagascar).

8. **Consider planting with species that meet specific social/economic/ecological goals**. Assuming the minimum ecological requirements are met, species can be

Characteristic	Description and Rationale
Growth rates	Fast biomass gain for carbon storage; rapidly forming tree canopy to shade out light-demanding, early successional vegetation; Plant species with varying growth rates so some establish quickly and others live longer
Growth form – e.g., herb, shrub, tree	Growth form(s) selected will affect vegetation structure and diversity
Tolerance of low nutrient soils and N-fixation	Able to grow and improve soil conditions in degraded sites
Tolerance of stressful and changing climatic conditions	Tolerant of variable temperature and moisture conditions to be able to establish in degraded sites and survive in a changing climate
Traits that attract fauna	Fruits that attract seed-dispersing fauna, nectar sources, or species that provide habitat structure for fauna
Conservation concern	Species that are rare and the focus of conservation efforts
Likelihood to establish naturally	Plant species that are unlikely to colonize naturally to increase diversity
Feasible to collect and propagate/ available in local nurseries	Increases cost efficiency and ease of restoration
Desirability as wood, non-timber forest products, or other economic or cultural reasons	Provides income, food, or other products, which increases the incentive for land-owners to plant and maintain vegetation

Figure 14: Potential characteristics to consider in selecting plant species for restoration (Modified from (4)).

chosen for their economic or cultural value, or carbon sequestration potential.

TOOLS AND RESOURCES

- Plant Functional Traits and Species Selection in Tropical Forest Restoration. Lachlan C. S., *Tropical Conservation Science*, 11(1), 2020.
- Agroforestry Tree Domestication: A primer. Dawson et al., *ICRAF: The World Agroforestry Centre*, 2012
- Restoring Ecosystem Services Tool (REST): A computer program for selecting species for restoration projects using a functional-trait approach. Rayome et al., *USDA: United States Department of Agriculture*, 2019.
- Preparing to Plant Tropical Trees. Longman, K. A., *Commonwealth Secretariat*, 1995.
- Tree Species Planted for the Atlantic Forest Restoration: A floristic and functional analysis (Espécies arbóreas plantadas na restauração da Mata Atlântica). Almeida et al., *LASPEF-UFSCar: Laboratório de Silvicultura e Pesquisas Florestais, 2020*. (In Portuguese, tables have English captions).
- Primer for Ecological Restoration. Holl, K., *Island Press*, 2020.


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SECTION 6:

MAINTENANCE FOR APPLIED NUCLEATION

Applied nucleation often requires maintaining both planted and naturally-establishing trees. Maintenance should support project goals, be included in budgets, and be aligned with monitoring to allow for adaptive interventions (1, 94). Applied nucleation aims to restore canopy cover with native forest species; at a minimum, maintenance in AN systems should facilitate native forest regrowth, but the amount of maintenance depends on project goals and local site conditions (1, 57). This section outlines key maintenance activities for AN systems. Resources for guidance on maintaining areas planted with trees and assisted NR apply to AN and are provided at the end of this chapter.

1. **Ensure that the area is protected** from stressors that could damage regenerating forests, such as fire, grazing, herbivory, and removing trees for harvest (unless harvesting select trees is part of the strategy). Site protection is essential to ensure long-term success. Maintaining fencing, firebreaks, and enforcing local land use rules are all important activities. In some places, rodent predation can also affect regeneration (as was observed in a GEF-CI project in the high Andes, also (95)). Protection from grazing (e.g., maintaining fencing) is particularly important in AN because the vegetation that grows between tree patches is often palatable to livestock, especially during the dry season when forage may be scarce elsewhere (52). Protection from fire is also key - vegetation between islands may be more flammable around islands, leading to increased tree damage on their perimeter (case example 5, Madagascar). Maintenance activities can be adapted to different environments and contexts: for example, 'green' firebreaks of planted inflammable vegetation can be used, which require less maintenance than bare soil firebreaks (96).

2. **Encourage the growth of planted and regenerating trees** in and between tree islands. In areas where trees seem to be regenerating well, protecting land might be sufficient. When highly competitive, sun-loving plants - like planted pasture grass - are present, periodic clearing before and after planting between and inside islands may be needed until both planted and regenerating seedlings are established. The duration of maintenance depends on tree growth rates and on-site vegetation, but in many tropical contexts mechanical clearing (e.g., with machete or other cutting instrument - avoid using fire and chemicals as these can damage regenerating trees) 2-4 times a year for 2-3 years is common (1, 58, 92). After canopy cover is established clearing is no longer needed because expanding islands shade out other vegetation. (As noted above, highly invasive shade-tolerant species - especially tree species - could mean that applied nucleation will not work as they will not be shaded out by expanding islands (14)).

   The general process for clearing between islands is: 1) identify the regenerating trees that should be protected, 2) clear vegetation around regenerating seedlings, and 3) apply fertilizer when/if necessary (1, 57). Clearing vegetation around planted seedlings can be challenging especially when trees are small. Carefully marking tree planting boundaries of islands can help to prevent accidentally cutting planted tree seedlings.

3. **Protect seed dispersers** from hunting and other threats. Seed dispersers are key for aiding in the natural regeneration process. This may involve working with local communities to limit hunting (1). This could also involve keeping cats or dogs out of restoration sites.

4. **Replant trees in islands** if a substantial number of trees die. A certain percentage of tree mortality and replanting should be included in the project budget.

5. **Control insects** that damage planted and/or regenerating trees (such as leaf-cutter ants) if necessary.

6. **Watering or fertilization** may be needed to enhance initial planted tree survival and growth in areas where water shortages exist or soil quality is low.

7. **Practice enrichment planting in regenerating sites to meet ecological and social goals**. In both plantation-style planting and AN, late-successional, large-seeded species tend to be in low numbers

or absent from restored plots (17, 22, 46). In Costa Rica, a 15-year study showed that AN and plantation-style plots both had a greater number of large-seeded tree recruits than natural regeneration plots, but much lower density of large-seeded species than nearby, older reference forests (45). These results show that resources for long-term maintenance and adaptive management are important for determining if enrichment planting is needed once the canopy is established (Box 3).

TOOLS AND RESOURCES

- Restoring Forest Landscapes through Assisted Natural Regeneration (ANR) – A Practical Manual. *FAO: Food and Agricultural Organization of the United Nations*, 2019.
- Application of Assisted Natural Regeneration to Restore Degraded Tropical Forestlands. Shono et al., *Restoration Ecology*, 15(4), 2007. (Provides detailed guidance for doing assisted natural regeneration in the field, including identifying and caring for regenerating trees).
- A Guide to the Restoration Opportunities Assessment Methodology (ROAM): Assessing forest landscape restoration opportunities at the national or sub-national Level. *IUCN: International Union for Conservation of Nature & WRI: World Resources Institute*, 2014.
- International Principles and Standards for the Practice of Ecological Restoration, Second Edition. Gann et al., *SER: Society for Ecological Restoration*, 2019.
- Guidelines for the Restoration, Management and Rehabilitation of Degraded and Secondary Tropical Forests. *ITTO: International Tropical Timber Organisation*, 2002. (Includes maintenance as a key step for successful enrichment planting practices. Maintenance activities can be adapted to different environments and contexts (such as the use of 'green' firebreaks, made up of planted inflammable vegetation, which require less maintenance than bare soil options)).

BOX 3: CHARACTERISTICS FOR TREE SPECIES IDEAL FOR "ENRICHMENT PLANTING" (MODIFIED FROM (96))

Regular flowering and fruiting; Wide ecological amplitudes; Tolerance to moisture stress; Larger-seeded species that don't establish naturally; Have a higher survival rate when planted under an open canopy; Threatened or locally threatened species; Species with high cultural value

If trees are to produce direct economic benefits (NTFP, timber) also consider:
Produce timbers of high value or NTFP; Rapid height growth; Good natural stem form; Free of pests and diseases; Low crown diameter

Non-tree species are also important for the ecology of many forests. Consider planting:
Epiphytes: slow to recolonize secondary forests, but play a big role in providing food, water, and climate control to canopy-dwelling organisms (28, 97); Forest shrubs or bushes of high ecological, economic or cultural value.

SECTION 7:

MONITORING

Monitoring AN is essential to guide management interventions and assess outcomes. Below we include AN specific guidance, including relevant indicators for monitoring. Many resources describe how to develop monitoring protocols for natural regeneration (General guidance in 1, 57, 94) and for forest restoration/ forest and landscape restoration more broadly (4, 31, 98). See also the tools and resources listed at the end of this section.

General Monitoring and Adaptive Management

1 Identify → what to monitor (develop criteria and indicators related to objectives);

2 Establish → threshold points where further intervention is needed;

3 Develop a sampling design (measure indicators of the selected criteria);

4 Collect → and analyze data;

5 Evaluate → results and communicate to stakeholders;

6 Re-evaluate the process in order to guide future efforts.

Figure 15: Key steps in monitoring and adaptive management. (*Adapted from Stanturf et al., 2017* (*pg. 67*).

DEVELOPING A MONITORING PLAN

A monitoring program starts in the planning stages of a project when the objectives and goals are defined. These should be paired with appropriate indicators to 1) assess if work is moving in a direction that meets some or all of the project goals, and 2) capture additional attributes important for project outcomes (Figure 1, Figure 15). The process of goal setting and monitoring should be developed in collaboration with landholders and/or larger community, and should be seen as a way to strategically engage them throughout the process. To the extent that monitoring and maintenance can provide training, capacity building and local employment, it can greatly strengthen long-term investment in and sustainability of the project (98).

POTENTIAL INDICATORS FOR AN PROJECTS

Indicators will stem from the criteria/goals/objectives of a specific restoration project. Several that could apply to AN projects with the primary objective of aiding and accelerating natural processes of succession are:

- **The survival and stem diameter (which can be used to calculate biomass) of planted trees.**
- **The number and species identity of newly established recruits in and between islands**. If few, additional interventions (like clearing around regenerating seedlings or planting additional trees) may be needed.
- **Percent canopy cover** at 3 years. If the canopy is not well established at that point, action should be taken to increase canopy cover, and cover should be monitored at regular intervals. A closed canopy is important for creating conditions that will allow later-successional species to establish.
- **Tree island spread (e.g., how far has the canopy expanded between islands)**. Even if a closed canopy is established within the island, if the islands aren't spreading then additional planting may be needed. Island spread can be measured as a change over time in the distance to the edge of the canopy from the bole of a planted tree on the edge of the planting.

- **Presence/absence of key plant species.** When appropriate, monitoring the presence of species that have been identified as important for either ecological or social purposes will be important. Note that if there are key species that should be included, they should be planted initially or via enrichment planting.

- **The overabundance of weedy or invasive species that might outcompete recruits**. This is a negative indicator that suggests further intervention is necessary.

- **Regenerating seedlings are diverse and representative of the species found in reference sites**. Comparing regenerating trees to reference forests is valuable to both understand how well AN is working to restore native forest, and contribute to research in this field (see section 9). Monitoring the proportion of wind vs. animal dispersed species is also helpful to understand if AN is successfully attracting dispersers to the site.

If supporting local livelihoods is a project goal, the following indicators could also apply:

- **Non-timber forest products** measured as 1) present at the site (potential harvests) and 2) actual amounts harvested (actual harvests/yields).
- **Number of local jobs created** and over what time period. This could include jobs related to planning, planting, monitoring,maintaining, and harvesting from restored sites.

- **Contribution of the project to household income** via wages for planting, monitoring and maintenance, and/or products harvested from the site.

- **Value and distribution (e.g., how many households, percent contribution to household income, measure of equity of distribution) of any payments for environmental services**, such as water or carbon sequestration?

TOOLS AND RESOURCES

- Monitoreo a Procesos de Restauración Ecológica Aplicado a Ecosistemas Terrestres. Aguilar-Garavito, M., & Ramírez, W. (Eds), *IAvH: Instituto de Investigación de Recursos Biológicos Alexander von Humboldt*. 2015.

- Implementing Forest Landscape Restoration: A practitioner's guide. Stanturf et al., *IUFRO: International Union of Forest Research Organizations*, 2017.

- Participatory Monitoring in Tropical Forest Management: A review of tools, concepts and lessons learned. Evans, K., & Guariguata, M. R., *CIFOR: Center for International Forestry Research*, 2008. (Describes a process for collaborative monitoring involving communities and other stakeholders, which could be appropriate in areas with communities who are actively using the land).

- International Principles and Standards for the Practice of Ecological Restoration, Second Edition. Gann et al., *SER: Society for Ecological Restoration*, 2019. (Contains basic guidance for a monitoring process, and notes that monitoring should begin in the planning phase of projects and be geared towards easy-to-measure indicators of success, a process that will be helpful by involving stakeholders).

- Primer for Ecological Restoration. Holl, K., *Island Press*, 2020. (Contains a chapter describing the process and main considerations for monitoring and maintenance for ecological restoration).


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SECTION 8:

LEARNING FROM PRACTICE – CREATING FIELD 'EXPERIMENTS'.

Despite its promise and performance as a restoration technique, there are still significant research gaps to inform AN practice. Planning implementation and monitoring in a way that allows data to be collected without compromising project outcomes would be extremely valuable to advancing the field. This section outlines six main research questions, and guidance for using field implementation to address them.

1. **What are the best combinations of tree species to use?** Little research has tested the impact of using different species combinations in tree islands (but see (85) and case example 3). Future work could test different species combinations with different functional traits.
    - What is the optimal balance of early versus late successional species in tree islands?
    - Are there significant benefits to be gained by adding more species?
    - Is there an added benefit to incorporating non-tree plants such as shrubs, herbs, and epiphytes in AN plantings?
2. **How important is planting species with animal-dispersed seeds to attract dispersers?** Past work has found that animals still disperse seeds to plots with no species that provide good fruit (22), and a minimal effect of planting wind vs. animal dispersed trees on seedling recruitment (99). But it stands to reason that food resources would increase the effectiveness of AN. More examples and comparisons are needed in different contexts.
3. **How do different planting configurations affect regeneration in and outside of tree islands?**
    - How do different tree island shapes affect ecological outcomes?
    - How does forest recovery compare in areas planted with 'tree islands' vs. linear strips?
    - Does the distance between tree islands affect the expansion of tree islands?
    - Does tree distance between planted trees within islands affect the expansion of tree islands?
    - What is the optimal spacing and configuration of tree islands?
    - Should it be equal spacing or clusters of tree islands?
    - How far apart can islands be spaced?
4. **How and how well does AN work in a range of tropical forest types?** (for example, high elevation forest, dry forest, mangrove forest)? Most research on AN has been from premontane or lower montane forests (47, 100). The questions about spacing could vary in different forest types or biogeographic regions.
5. **How well does AN work at larger scales** (i.e., ideally areas greater than 5000 ha); but mid-scale studies (>100 ha) would also be useful). There are currently no studies that look at how well AN works at larger scales.
    - What landscape conditions are most appropriate for using AN at scale?
    - What patch size to spacing ratios are best for large-scale AN?
6. **How fast do nuclei spread in different ecosystems?** A potential way to assess this would be to use drone flyovers and images to estimate canopy area in different years. This will be most useful in the early years when it is clear what is and what is not canopy.

SETTING UP AN AS AN APPLIED EXPERIMENT

Each restoration effort can serve as an experiment to inform future work. Often projects are implemented without planning or follow-up to learn from practice. But as part of a monitoring program, projects can improve their ability to contribute to the field with a minimal amount of additional effort. The objective must be integrated in the planning stage.

BASIC CONSIDERATIONS FOR SETTING UP AN AS AN APPLIED EXPERIMENT:

1. To understand how well AN works as compared to other common restoration methods, **implementation should include three basic treatments:**

   A. A naturally regenerating control (NR),

   B. An area planted using standard plantation-style plantings and/or strip plantings. Species used and other methods should be recorded.

   C. An area with AN treatments. The design should be recorded as well as the species used.

Costs should also be recorded for each technique. Note that the area of each does not need to be the same - even small areas of NR and plantations can be used for comparison with AN.

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2. **The treatments must be applied in areas with similar environmental characteristics**, to the degree possible, such as land use history, distance from forest remnants, slope, aspect, and elevation. All of these attributes should be recorded, along with the forest type, rainfall, and other relevant ecological site attributes. Alternatively, there should be enough replication (sites) that it can account for variability in the landscape.

3. **To understand different configurations of tree islands** (for example, different distances between islands) **or planted species assemblages** (e.g., using different combinations of species), AN plots should be divided into different types of AN. Also see case examples at the end of this guide.

4. **At a minimum, ecological experiments will require monitoring:**

   A. Canopy cover

   B. Number and species identity of regenerating trees at five years (and ideally longer intervals, e.g., 10-15).

   Ideally, ecological experiments would also:

   C. Identify regenerants by dispersal mechanism to understand the effect of AN on successional processes. It could also be useful to classify “successional status” if the information is available.

   D. Monitor other aspects of forest recovery, particularly if there is local expertise that can be used (e.g., bird, plant, or arthropod surveys).

   E. Record the cost of implementing and maintaining treatments, including supplies, labor, and transportation.

5. **To date, the social elements of applying AN have not been systematically examined.** It would be useful to collect data on:

   A. How this technique is perceived by local communities,

   B. How quickly and under what circumstances it is adopted (for example, on private farms),

   C. The specific challenges to implementing AN in a range of contexts, and

   D. The outcomes for livelihoods and land use.

Recording the process for implementation is an important step toward obtaining social data. Participatory appraisal techniques - important for the planning phases in many contexts - can also be used to assess baseline conditions and measure follow-up after implementation. Even if it is not possible to set up projects with an experimental component, regular monitoring using standardized procedures is important to learn from individual projects and compare across projects.

SECTION 9:

RESOURCES

Below is a list of the tools and resources provided in the other sections of this guide, plus other general resources.

RESTORING FORESTS FOR CLIMATE CHANGE MITIGATION. *CI: CONSERVATION INTERNATIONAL*, FORTHCOMING.

Society for Ecological Restoration (SER) Project Database. *SER.*

This resource provides a database of restoration projects across different regions and ecosystems and is intended as resources for potential stakeholders and practitioners. The database is searchable or can be filtered by biome, region, country, ecosystem, or cause of degradation. Project descriptions generally include an overview, the time frame, a definition of the problem, the planning and design, project activities and outcomes, key lessons, long-term management, and funding.

Restoration Opportunities Assessment Methodology (ROAM). *IUCN: International Union for Conservation of Nature & WRI: World Resources Institute.*

ROAM provides a framework, process, and tools to help identify priority areas for restoration at the national or sub-national level and analyze them for the best type of intervention. For each possible intervention type, an assessment can quantify costs and benefits, estimate carbon sequestration values, analyze financing options, determine 'restoration readiness', and address existing policy or institutional blocks so as to improve restoration planning and implementation.

Guidelines for Forest Landscape Restoration in the Tropics. *ITTO: International Tropical Timber Organization, 2020.*

These guidelines, building on the 2002 ITTO Guidelines for the Restoration, Management and Rehabilitation of Degraded and Secondary Tropical Forests, provide policy and technical expertise for those implementing or interested in FLR. A number of guiding elements are presented to structure interventions and recommended actions so as to follow the six core principles of FLR. It also includes 18 case studies of restoration from across tropical regions, and there is an affiliated policy brief.

Primer for Ecological Restoration. *Holl, K., Island Press, 2020.*

This book introduces the basics of planning, monitoring, and adaptively managing an ecological restoration project. It explains abiotic factors such as landforms, soil, and hydrology and covers other topics such as invasive species and legal and financial considerations. Further recommended readings or references for each chapter, a list of case studies, and other learning resources are included as well.

Implementing Forest Landscape Restoration: A practitioner's guide. *Stanturf et al., IUFRO: International Union of Forest Research Organizations, 2017.*

A guide for systematic FLR approach from implementation to monitoring mainly at the landscape level with a focus on climate change mitigation and adaptation presented by the IUFRO. This provides practical guidance for practitioners and stakeholders in a local context. It is organized in modules that cover "getting started", navigating governance challenges, designing a restoration project, technical aspects of implementation, monitoring, and more.

Sustainable Forest Management (SFM) Toolbox. *FAO: Food and Agricultural Organization of the United Nations.*

The FAO's SFM Toolbox is a hub of information for stakeholders invested in sustainable forest management. It includes a range of tools, cases, and other resources organized into modules. Modules include technical topics, such as agroforestry, forest and landscape restoration, or forest management planning, along with non-technical modules on forest governance, collaborative conflict management, and more.

The Forest and Landscape Restoration Mechanism. *FAO: Food and Agricultural Organization of the United Nations.*

The FAO established the Forest and Landscape Restoration Mechanism (FLRM) in 2014 to support FLR planning, implementation, and monitoring activities in countries as a contribution to achieving the Bonn Challenge and Aichi Biodiversity Targets. The FLRM includes an interactive online communities of practice to facilitate communication and knowledge sharing, a library of resources, and opportunities to take courses.

Reforestation, Nurseries, and Genetic Resources. *USDA: United States Department of Agriculture, Forest Service and Southern Regional Extension Forestry*

This program, sponsored by the US Department of Agriculture, Forest Service, provides information for those growing seedlings for forestry or conservation purposes. Their section on Tropical Nurseries includes a list of publications and various manuals for guiding work with tropical plants.

Link to case study references document: https://docs.google.com/document/d/1sYnH0GUfCjBxpBWNZVCR-TceKU12C8A2eOCVA084-10/edit?usp=sharing


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SECTION 10:

CASE EXAMPLES

CASE EXAMPLE 1:

Tree Islands in tropical premontane forest in southern Costa Rica. Karen Holl (University of California, Santa Cruz); Rakan Zahawi (Lyon Arboretum and School of Life Sciences, University of Hawaii at Mānoa).

Context: This experiment was started in southern Costa Rica in 2004-2006 to compare the long-term ecological efficacy of applied nucleation to natural regeneration and to more intensive plantation-style tree planting. The study was primarily set up as a scientific experiment, but the authors worked with numerous local landholders who agreed to allow the experiment to be established on their land and have been involved in various educational outreach programs in the region. The study region is a primarily agricultural landscape with extensive pasture lands and some coffee farms with interspersed remnant forest patches. The sites used in the experiment were all previously used for agriculture for more than 18 years (mainly cattle grazing or coffee production), and at the time of implementation were covered in exotic grasses or a mixture of grasses, forbs, and ferns.

Implementation and applied nucleation design and costs: The experiment was conducted in the premontane forest zone in southern Costa Rica at sites ranging in elevation from 1100-1430 m elevation and receiving 3500-4000 mm of rainfall annually. A total of 18 1-hectare sites were originally established, with 12 still active as of 2020. At each site, three 50 x 50-m plots were established, each with one treatment: applied nucleation, plantation tree-planting, or natural regeneration with no intervention (Figure 1). There were three different sizes of tree islands planted within each applied nucleation plot (4 x 4, 8 x 8, and 12 x 12 m). Four tree species were planted, two native species, *Terminalia amazonia* and *Vochysia guatemalensis*, and two naturalized, nitrogen-fixing species commonly used in intercropping systems, Erythrina poeppigiana and Inga edulis (Holl et al., 2017, 2020). These four species were selected based on 1) high survival and growth rates as well as providing substantial canopy cover in their first few years, 2) availability in local nurseries, and 3) common usage in agroforestry systems or other restoration in Central America (Holl et al., 2011). Seedlings were 20-30 cm tall at the time of planting. In total, 313 seedlings were planted in plantation plots, 86 in tree islands plots, and 0 in control plots. Vegetation was cleared from the plots before planting and continuously cleared at approximately 3-month intervals for the first 2.5 years to assist the growth of seedlings over grasses. Holl and Zahawi (2018) estimate planting and maintenance costs for applied nucleation as US$357-620 per hectare versus US$1,462-2,282 per hectare for plantations.

The authors have collected extensive data over the past 15 years on vegetation recovery including planted tree survival and growth; woody vegetation recruitment, survival, growth and structure; and epiphyte species richness. They have also collected data on abundance, richness, and composition of birds, bats, and leaf litter insects, as well as seed dispersal, insect herbivory on seedlings, and litterfall biomass and nutrients, the results of which are summarized in Holl et al. (2020)

Outcomes: The results showed that applied nucleation was much more effective than the natural regeneration plots and similar to the plantation plots, in terms of canopy cover, species recruitment, and other key metrics (Holl et al., 2020). Natural regeneration had the lowest density of large animal-dispersed tree seeds and recruits, and reference forests

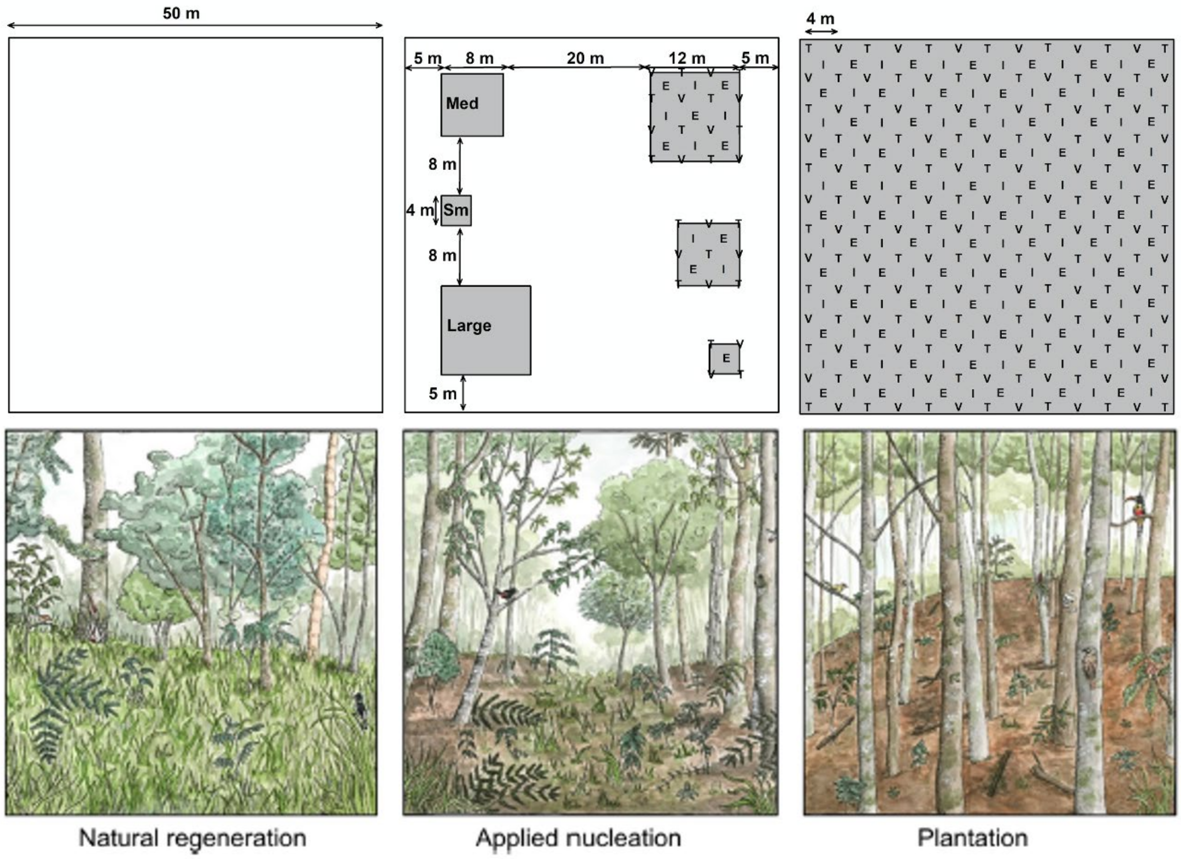

Figure 1: From Holl et al. (2020). Top panels detail the original planting design and bottom panels illustrate the plots after 15 years showing both planted and naturally recruited vegetation. In top panels gray areas were planted with *Erythrina poeppigiana* (E), *Inga edulis* (I), *Terminalia amazonia* (T) and *Vochysia guatemalensis* (V). Sm = small; Med = medium. *Artist credit: Michelle Pastor*

Figure 2: Applied nucleation plot. Vegetation is a mix of planted and naturally recruiting trees. *Photo credit: Karen D. Holl*

surrounding the sites the highest while applied and plantations both were at intermediate levels (see Figure 3). After 15 years there were still few late-successional species found within all of the treatment plots, but this largely indicates the evolving and multi-decadal process of forest regeneration. Bird and bat abundance, leaf litter arthropods, epiphyte richness, litterfall production, and litterfall nutrient inputs were all similar or equivalent between plantations and applied nucleation plots, and higher than the natural regeneration plots (Figure 3).

Results of this study and of Zahawi and Augspurger (2006), who studied applied nucleation in tropical forests in Honduras, show that larger tree nuclei (64 and 144 m2 planted area) have much higher visitation rates by birds, dispersal of animal-dispersed seeds and seedling recruitment than smaller nuclei (4 and 16 m2)(Fig. 4A&B). This result was likely due to greater percent canopy cover in large and medium nuclei, which both attracts seed dispersers and shades out light-demanding and highly competitive pasture grasses). Despite planting only 27% the number of tree

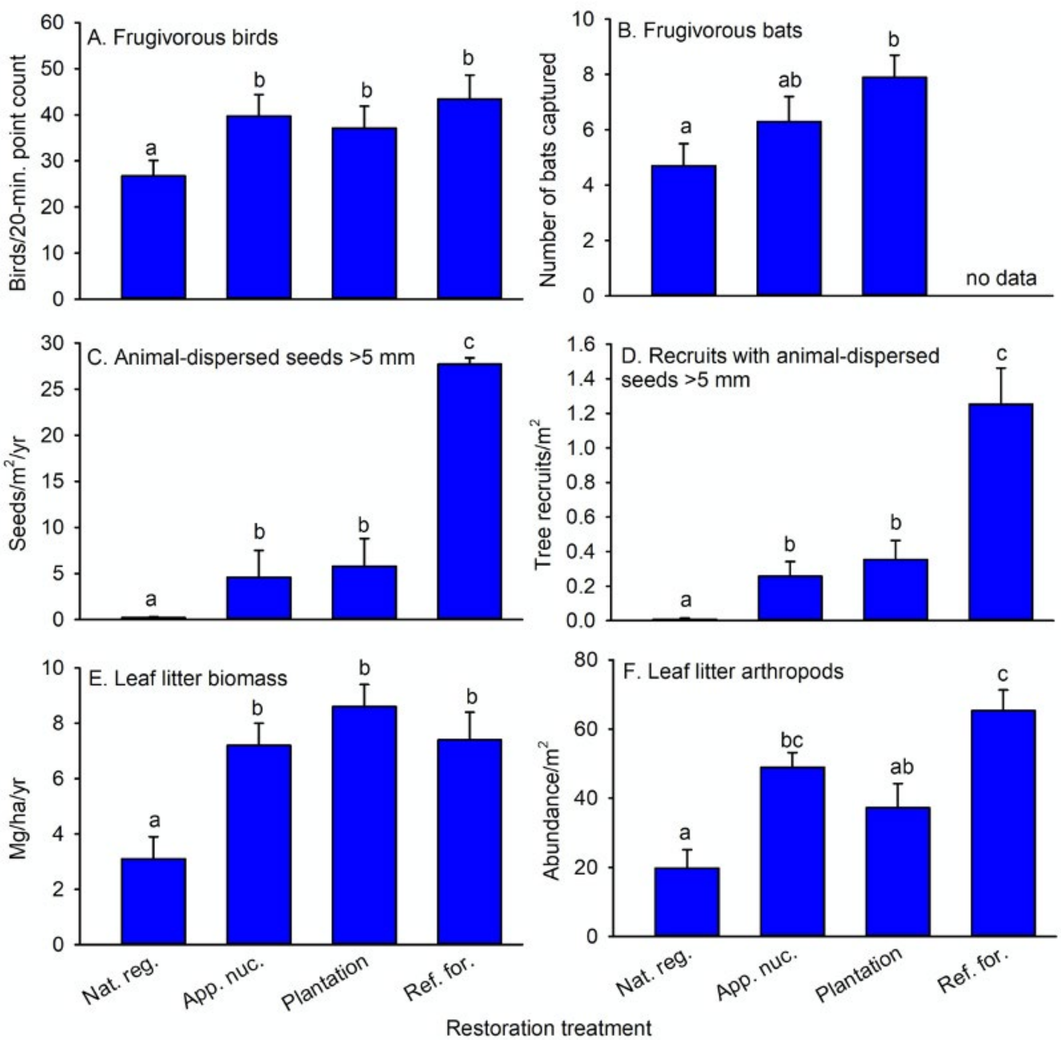

Figure 3: Modified from Holl et al. (2020). Responses of ecological variables to forest restoration treatments. (A) Frugivorous bird abundance; (B) Frugivorous bat abundance (C) Abundance of animal-dispersed seed >5 mm (D) Abundance of recruits with animal-dispersed seeds >5 mm; (E) Leaf litter biomass (F) Leaf litter arthropods in 2012. Values are M ± 1 SE. Means with the same letter do not differ significantly using Tukey's multiple-comparison test among treatments.

seedlings in applied nucleation plots, canopy cover >2 m had increased substantially to 45.5 ± 9.0% in these plots, as compared to 14.2 ± 6.1% in natural regeneration plots and 78.2 ± 9.1% in plantation plots after 7-9 years.

Lessons learned: Overall, this study demonstrated that applied nucleation can improve tree recruitment and species diversity in comparison to natural regeneration, with similar ecological outcomes to plantation-style tree planting, but at a much lower cost. Surrounding forest cover was found to have little effect on recruitment and instead local site conditions were deemed a larger factor, indicating that applied nucleation could potentially be effective in different landscape contexts (Holl et al. 2017).

While ecologically effective, some landholders' perceived applied nucleation and natural regeneration as "messy" and not as "productive" a use of land as planting the entire area with trees. We had to be vigilant about preventing livestock entry, particularly in natural regeneration and applied nucleation plots, where the more abundant grass was perceived by farmers as unused. Hence, applied nucleation is probably most appropriate in large landholdings that are designated for conservation purposes and will require extensive discussions with landholders to be used in working landscapes.

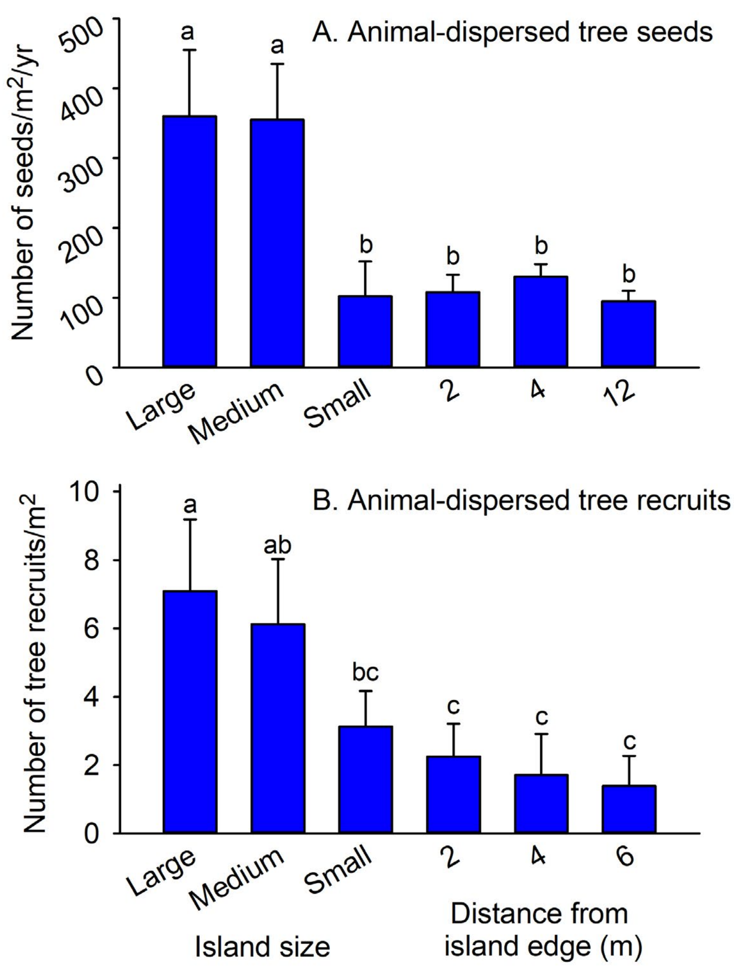

Figure 4: Modified from Holl et al. (2020). Number of (A) animal-dispersed seeds, (B) tree recruits.

For more information and publications see holl-lab.com/tropical-forests.html and you can view the project video in [English]() or [Spanish]().

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CASE EXAMPLE 2:

Nucleation To Assess The Effect Of Plantation Density And Leaf Size On Gorse (Ulex Europaeus) Regeneration And Plantation Performance. Iván Rodríguez (Universidad Distrital); Juan Garibello (Instituto Humboldt); Ángela Parrado (Universidad Distrital).

Context: The experiment was conducted in the hills east of Bogotá, Colombia at 3200 m.a.s.l., in the ecotone between upper montane cloud forest and lower Páramo shrubland. Annual precipitation is 1200 mm and soils are volcanic. The site is owned by the municipality but was illegally occupied for potato and cattle production from 2000 to 2012. As a result, there was a severe invasion by gorse (Ulex europaeus) over 19 Ha. Management goals include eliminating gorse thickets in different states of development, mitigating gorse regeneration, introducing native vegetation that can outcompete gorse, and facilitating the participation and empowerment of local community members.

Implementation and applied nucleation design and costs: Our experiment was established in 2017. Prior to this, starting in 2012 the local government had been restoring the site by periodically clearing gorse and planting native trees. We used applied nucleation based on its cost-effectiveness, and the poor performance of trees previously planted (in the traditional pattern with five to ten meters between individuals). The study area covered 19 ha, and nucleation was applied over 5 ha and included 200 'tree islands' or nuclei. Each circular island was 6 m in diameter with a distance of 6 to 10 m between islands (Figure 1), and densely planted with trees. We installed six replicates of each treatment with a combination of two factors: 1) plantation density (1.1 m and 0.9 m apart) and 2) composition of species assembly according to leaf size. Gorse regeneration can be affected by dense plantations (Díaz & Vargas, 2009) - so, we tested different planting densities: 0.9 and 1.1 m between planted trees (Figure 2). The lower density uses 33% fewer trees and reduces the costs of implementation. We planted native tree seedlings provided by government-run local nurseries. We used leaf area or size – initially assessed by eye – as a proxy for other traits like plant size (Pérez-Harguindeguy et al., 2016) which in turn might be linked with competitive ability (Reynolds, 1999). Islands were planted with three treatments of leaf size: (1) large leaved species (=36.7 ; S.E.= 4.7 cm-2) , (2) small

Figure 1: Panoramic view of nuclei and the study site at the border between Bogotá urban area and its east hills (Photo by Iván Rodríguez in 2018 one year after plantation).

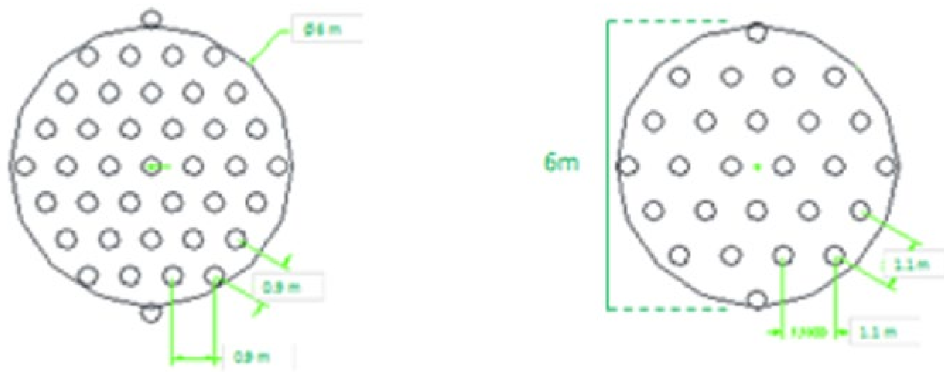

Figure 2: Diagram of planted nuclei. Left. High density nucleus (0.9 m between seedlings). Right. Lower density nucleus (1.1 m between seedlings)

leaved species (=3.2 ; S.E.= 0.5 cm-2)and (3) a combination of both (=22.0 ; S.E.= 2.6 cm-2).

We also established control plots where no planting occurred. In both control sites and tree islands, gorse was removed just before planting, 15 months later and two years later after monitoring. The cost of establishing 200 nuclei was approximately US$ 23,000. This amount includes staff, propagation and transport of trees, but not monitoring.

To implement its Restoration Program in Bogotá, the local government hires a vulnerable population which includes homeless, unemployed, afro, indigenous and LGBT minorities. Thanks to this approach, several of the people employed have obtained technical degrees in environmental subjects to move up within the Program and advance their careers.

Outcomes: social and ecological We measured gorse regeneration, tree recruitment, and performance of planted individuals. After data analyses with linear models, below are ecological results 24 months after planting:

- AN worked to increase tree recruitment: saplings were recruited under tree islands, but not in naturally regenerating areas.
- Different treatments had different levels of tree recruitment and reduced grass cover: High-density nuclei with large leaved species (= 23.7; S.E = 8.4) and lower-density nuclei with combination of leaf sizes (= 7.2; S.E = 2.9 shoots per nuclei) had the highest abundances of tree recruits. Grass cover was also reduced by 11 to 29% in planted nuclei compared to natural regeneration ($p < 0.0001$[2]). Naturally regenerating controls are co-dominated by non-native grasses *Holcus lanatus* and *Pennisetum clandestinum*.
- Trees grew taller in lower density nuclei with larger leaved species (= 100.8; S.E = 9.6 cm) and were shorter in dense nuclei with small leaved species (= 56.7; S.E = 2.9 cm). Trees in all other treatments were similar in height (= 75.6; S.E = 2.7 cm).[3]

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[2] *after linear regression with binomial distribution of errors*

[3] *according to paired comparisons after linear regression (F= ; 7.194 p<0.0001).*

- AN increased gorse recruitment compared to naturally regenerating controls, likely because removing grass and disturbing soil for tree planting created favorable conditions for gorse.

- Of the AN treatments, nuclei with lower density and small-leaved species have the best potential to keep gorse regeneration at lower levels (Figure 3).

- Restoration at the study area has employed approximately 120 people from vulnerable minorities since 2017. Thirty high school students also participated to develop research skills and commitment with environmental issues (Figure 4), and over 20 groups of local community members were trained to control gorse outside the study area, and also to detect and report fires.

Challenges and lessons learned: Advice based on these findings for future AN work.

- Less dense nuclei (1.1m planting density) are better at controlling gorse regeneration and have faster tree growth rates. Less dense nuclei also cost ~30% less than denser nuclei - but because of the positive social impacts of the effort, we recommend planting larger areas with the same resources. Gorse regeneration was lower under small-leaved species but species with larger leaves seem to grow faster. Additional monitoring is necessary to determine if there is an ideal species assemblage.

- Cows were occasionally spotted at the sites - negotiations with some members of the local community are needed to stop livestock entry.

- Because of the social impact of generating employment through its restoration program, the government of Bogotá La

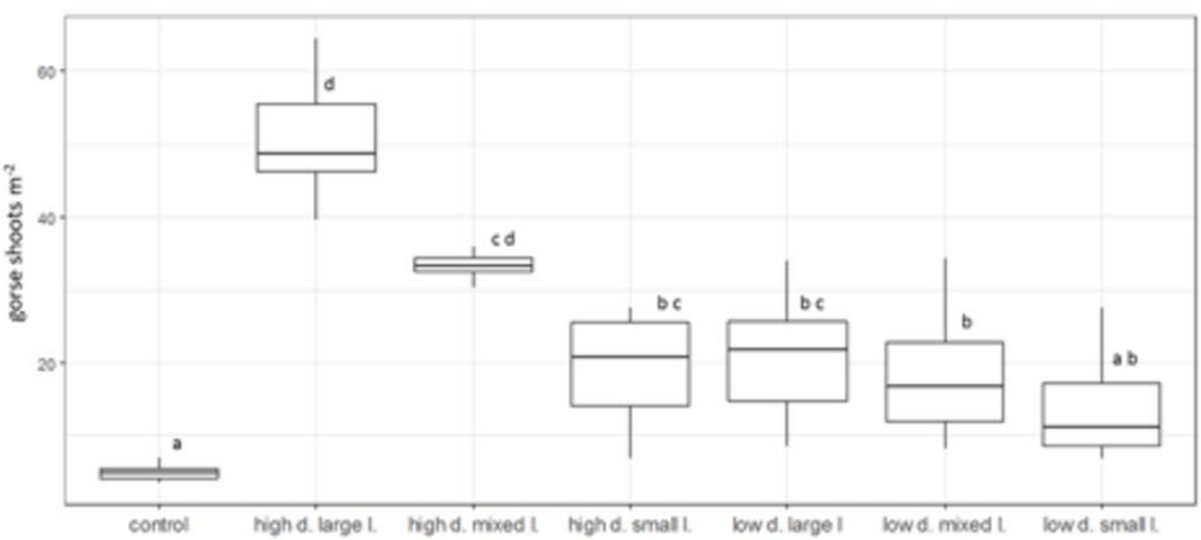

Figure 3: Boxplot of density of gorse shoots at control and planted nuclei two years after planting; In horizontal axis “d” stands for density and “l” stands for leaves of planted seedlings; “mixed” is the combination of both types of leaves. Letters indicate differences after post hoc Tukey´s test comparisons.

recently increased the financial support to the agencies implementing the program (Gobierno de Bogotá, 2020), keeping with the trend of sustained increases since the restoration program was created in 2000 (Murcia et al., 2017).

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Figure 4: High school students planting nuclei at the study area. (Photo by Juan Garibello)

CASE EXAMPLE 3:

Applied Nucleation To Recover Populations Of Locally Threatened Timber Species. Juan Garibello (Instituto Humboldt); Iván Rodríguez (Universidad Distrital); Ignacio Barrera (Universidad Javeriana).

Introduction and context: Restoration was undertaken in the low montane tropical forest (1200-1350 masl) at the west side of Serranía de Los Yariguíes, Colombia, declared a National Park in 2005. Restoration was part of a corporate offset for the construction of a hydroelectric dam in the Province of Santander in Colombia. Annual precipitation is ~2,500 mm. The whole region was greatly impacted by the conflict between guerrillas, paramilitary groups and Official Forces. Land was cleared in 1977 and was used for agriculture - cattle breeding, and crops of cacao, coffee, avocado and citrus fruit - until 2012 when the National Park Service bought the farm. From 2012 to 2014, the site was affected by poaching and occasional logging.

We restored two different areas: 1) old fields (former paddocks), and 2) woody vegetation (hereafter secondary forest) at different stages of recovery. Together with the local community, we established two main goals: 1) Recover populations of species threatened by logging (in forests) and 2) in the old fields, establish a fully functional secondary forest by 2025. We compared the performance of three threatened tree species in secondary forest and in nuclei planted in old fields. We chose nucleation over a traditional plantation pattern primarily because it was a more cost-effective way to outcompete non-native grasses through the quick generation of a dense canopy.

Implementation and applied nucleation design and costs: The project was implemented between 2014 and 2016, in two sites located in the same watershed. A NGO based in Bogotá was in charge of the implementation under the supervision of the National Park Service and the company responsible for the offset. Local communities were hired according to governmental policies for planting, seed collection and seedling production but joined the project earlier to reconstruct land-use history and define restoration priorities and strategies.

We established 48 nuclei in an old field (11 - 13 ha) surrounded by secondary and mature forest. Nuclei were 25-m diameter circles (area 491 m2), planted with 567 seedlings from 9-12 species, and placed 30 to 40 meters apart. Planted trees were spaced 1 m apart to quickly create canopy cover that could outcompete non-native grasses Megathyrsus maximus and Brachiaria radicans. 96% of seedlings were pioneer species; the remaining 4% were commonly logged species that locals identified as threatened from overexploitation. Grasses were cleared before planting and once a month for three months after planting (Kettenring & Adams, 2011; Gaertner et al., 2012; advice from community members). We planted different species in four different types of nuclei: Type 1 - species abundant at forest edges and gaps; Type 2 - treelets commonly colonizing old fields; Type 3 - Fabaceae trees commonly found in secondary forests; and Type 4 - (mixed) combining species from all the others (Table 1). In secondary forests, threatened species were also planted 10 m apart in mono-specific rows. Implementation of the whole project was US $ 824,440 (about $2550/ha) (currency exchange rate US$1 = 3,748 Colombian pesos; 323 ha; planting of 102,000 seedlings). Monitoring was approximately US$51,500.

	Nuclei 1	Nuclei 2	Nuclei 3	Mixed nuclei
Pioneer species	*Heliocarpus americanum* (tr) *Solanum aphyodendrum* (tl) *Urera baccifera*(tl)	*Miconia sp.*(tl) *Piper aduncum* (tl) *Vismia baccifera*(tl)	*Erythrina poeppigiana*(tr) *Inga marginata*(tr) *Inga* sp.(tr)	Species included in all other nuclei
Target species	*Carapa* cf. *guianensis* (tr) *Caryodaphnopsis* sp.(tr) *Margaritaria nobilis* (tr) *Matisia* cf. *cordata* (tr) *Nectandra* sp. (tr) *Tabebuia rosea* (tr)			

Table 1: Species assemblages forming different types of nuclei at the study area. (tr) stands for trees and (tl) stands for treelets.

Outcomes: social and ecological:

- 19 to 26 months after planting, nuclei with canopies mainly formed by Heliocarpus americanus and nuclei co-dominated by Fabaceae trees (Inga marginata, Inga sp. and Erythrina poeppigiana) were more effective at facilitating survival of our target species compared to nuclei formed by treelets which commonly colonize old fields (Miconia sp., Piper aduncum, Vismia baccifera among others) and nuclei including all aforementioned species (Table 2).
- Target species survival (Carapa cf. guianensis, Margaritaria nobilis and Nectandra sp.) was similar between successful nuclei and secondary forest, but nuclei promoted faster growth (Figure 1).
- The project including these outcomes involved 121 people from local communities. Their participation in selecting plant species and designing the restoration strategies was a key part of project success (Figure 2).

Challenges and lessons learned: Advice based on these findings for future AN work.

- Planting nuclei with tall and fast-growth tree species worked better than species that colonize old fields and promote the survival and growth of target species.
- Nuclei size of 25 m diameter, plantation density of 1 m between trees and several clearings of invasive species produced good results.
- Secondary forests are suitable to promote the survival but not growth of our target species. Nevertheless, we maintain that this vegetation should be also included to recover populations of this type of species as a way to contribute to forest function.

A video in Spanish describing the project is available at https://youtu.be/k7_jvheKXRo

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	Secondary forest	Nuclei 1	Nuclei 2	Nuclei 3	Mixed nuclei
Carapa cf. *guianensis*	0.87 (30)	1.00 (20)	0.56 (16)	1.00 (20)	0.40 (20)
Margaritaria nobilis	0.67 (30)	1.00 (20)	0.60 (40)	1.00 (20)	0.48 (40)
Nectandra sp.	0.87 (30)	1.00 (20)	0.45 (40)	1.00 (20)	0.55 (40)
Total	0.80 (90)	1.00 (60)	0.53 (96)*	1.00 (60)	0.49 (100)**

Table 2: Fraction of surviving trees of locally threatened species in different types of vegetation and number of planting spots assessed (in brackets) two years after plantation. * = p<0.05 and ** = p<0.01 after linear regression with binomial distribution of errors in which survival in secondary forest was compared with survival in each type of nuclei established in a 10-ha old field.

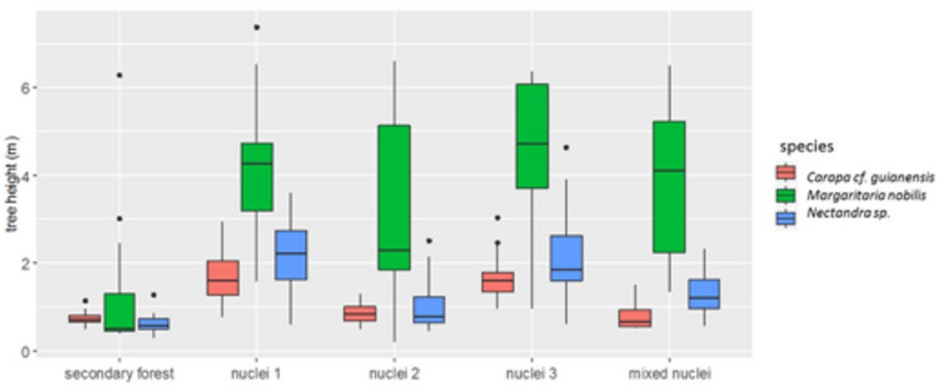

Figure 1: Boxplot with height of trees of species locally threatened in secondary forest and different types of nuclei differentiated by composition. Trees at nuclei 1 and 3 are taller than trees in secondary forest according to linear regression (p values < 0.0001) after two years of planting.

Figure 2: Members of local community processing seeds and selecting species for restoration of locally threatened species (Photo by Angélica Cogollo)

CASE EXAMPLE 4:

Applied Nucleation To Restore Riparian Forest At Maranhão University School Farm, Brazil

Guillaume Xavier Rousseau[1] and Danielle Celentano[1,2]

Context: This case describes applied nucleation efforts by Maranhão State University, São Luís, Maranhão State, Brazil. The climate is tropical with dry summer (As) and the original forest cover is open riparian Amazon rainforest. Nonetheless, the Paciência river has not been permanent at the site since the 1980s. Historically land was used for shifting agriculture but was converted to intense agriculture from 1985 until 2004, which suppressed forest vegetation and degraded the soil. From 2005 to 2012, the land was abandoned, and spontaneous forest regeneration was interspersed with grass and accidentally burned about every two years. Maranhão State has a one million Ha forest cover deficit according to the Brazil forest code (Brazilian Federal Government, 2012; Soares et al., 2014) and riparian forests are highly degraded which lead to soil and river degradation, and water shortages (Silva Junior et al., 2020). Restoring forest cover in the region is vital, but locally adapted techniques are missing – particularly low-cost techniques for small farmers. This project aimed to test restoration methods adapted to the region that could also be attractive for small farmers.

Implementation and applied nucleation design: Applied nucleation (AN) was applied over an area of 0.54 ha, along with Agroforestry System (AFS) treatment and control Natural Regeneration (NR) plots in a complete block design with six replicates (total 18 plots, 0.09 each, 1.6 Ha total) (Fig. 1). The AFS aimed to mimic natural succession with a mix of agricultural annual crops and perennial shrubs and trees of interest for local farmers (Celentano et al., 2020), identified through work in nearby on-farm AFS plots, where smallholders participated in designing restoration and choosing species. This partnership allowed for knowledge sharing and improved both scientific and farmer initiatives.

The site had a heterogeneous gradient of natural regeneration (Fig. 1b), and tree islands were placed at a regular distance (20 m) in areas with both low and high natural regeneration. The AN plots were randomly distributed over the 6 blocks of the experiment and consisted of four tree islands (2-m diameter) with 13 seedlings separated by 0.5 m and arranged in a cross. Ceiba pentandra (Ceiba) was always planted at the center (Fig. 2). Other species planted were: Handroanthus sp., Anacardium occidentale (Cashew), Moringa oleifera (Moringa), Gustavia augusta (Jeniparana), Hancornia speciosa (Mangaba), Inga edulis (Inga), Schizolobium amazonicum (Paricá), Mimosa caesalpiniifolia (Sabiá), Samanea tubulosa (Bordão de velho), Talisia esculenta (Pitomba). Cajanus cajan (Guandu), Bixa orellana (Urucum) and Manihot esculentum (Manihot) were sown as seeds or cuttings to protect seedlings and produce mulch. Islands were weeded two times per year during three years after planting. Control plots (NR treatment) were only maintained through cattle exclusion and the firebreak maintained around the entire experiment (Fig. 1). Primary forest reference sites no longer exist in the São Luís Island, and existing old growth patches had not been inventoried (Serra et al., 2016).

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Social and ecological outcomes: Despite three accidental fires and high seedling mortality (70%), the experiment was a 'success': AN allowed for quick re-establishment of native vegetation (Fig. 1 and 2). AN accumulated 11 (± 8) t.Ha of carbon in biomass (2012-2018) and had higher plant (tree and shrub) richness (mean 12±2 sp. per plot) than NR (4±2) or AFS (8±3). Nucleation provided both structural restoration and species enrichment. AN had a greater impact in terms of forest recovery in areas where little natural regeneration had occurred, but also increased species richness in areas with higher natural regeneration. The restoration experiment results have attracted much interest recently, and have been published in undergraduate projects, MSc. theses, and a scientific paper (Celentano et al., 2020). The site is regularly visited by students, government agents, farmers and civil society organizations. The main outcome of the project is the reappearance of a permanent spring in 2017 in the ancient river course that crosses the area under restoration.

Lessons learned: Advice based on these findings for future AN work: AN served different functions depending on the degree of regeneration prior to implementation. Where there had been low NR initially, islands helped establish vegetation structure and diversity, but in areas with more NR their main effect was enrichment. In large-scale restoration efforts, the choice of species should be fine-tuned to consider the heterogeneity of the area to be restored. A natural gradient or irregular natural regeneration patches are often present as well as small topographic variation that affects the development of seedlings. To consider the

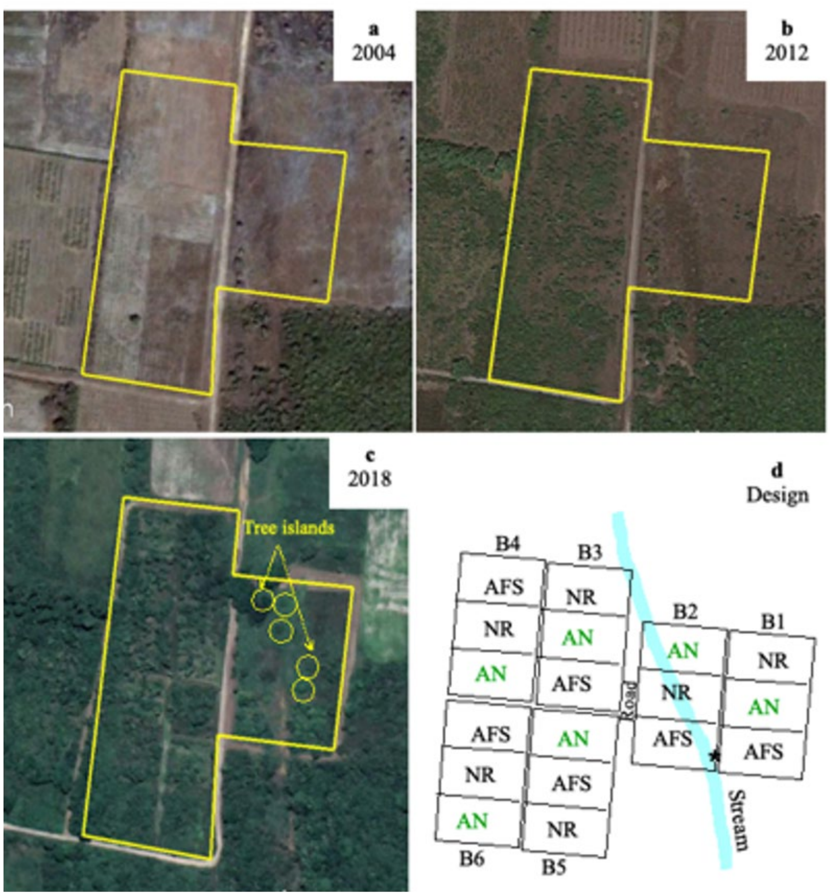

Figure 1: Land cover of the experimental site: a) 2004 last agricultural use; b) 2012 experiment installation; c) 2018 last monitoring; d) experimental design with stream and newborn spring (*) location (Applied Nucleation=AN, Agroforestry Systems=AFS, Natural Regeneration=NR).

spatial variations and adjust the choice of species and planting design to them would optimize the outcomes, therefore reducing total costs. Applied Nucleation is particularly well adapted for this purpose as tree islands can easily be positioned and species composition adjusted.

Controlling cattle and fire were the biggest challenges overall. Even inside the School, the community was not on board with conservation and restoration measures. Involving neighbouring communities as much as possible at the earliest steps of project design and installation is key. Community interest is also directly related to evidence to support the success of the restoration - showing initial results are important but recognizing that work will continue to innovate and change.

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Figure 2: Tree island development with different canopy openings: a) open canopy 2016; b) semi-closed canopy 2016; c) open canopy 2018; semi-closed canopy 2018.

CASE EXAMPLE 5:

Adapting Applied Nucleation To Wildfire Threat In Eastern Madagascar. J. Leighton Reid (School of Plant and Environmental Sciences, Virginia Tech); Donald Matthew Hill (Green Again Restoration, Department of Forest Resources, University of Minnesota); Jean François Solofoniaina Fidy (Parc Ivoloina Madagascar Fauna and Flora Group); Lee Frelich (Department of Forest Resources, University of Minnesota); Rebecca Montgomery (Department of Forest Resources, University of Minnesota).

Context: Madagascar's restoration needs are acute. This tropical island is smaller than Texas but houses 5% of the world's known species, 90% of which are found nowhere else on Earth. Deforestation is rampant in the narrow band of rain forest on the eastern third of the island. If deforestation continues at the current rate, there will be no rain forest outside of protected areas by 2080. One of the critical challenges for forest restoration in Madagascar is resource scarcity. Madagascar is among the world's economically poorest countries. Land managers are interested in restoration strategies like applied nucleation that may reduce project costs.

Our restoration project was done on the east coast of Madagascar, 14 km northwest of the city of Toamasina (-18.051966° lat, 49.350280° lon). This site is within the historic distribution of lowland rain forest, which until recently covered the island's east coast. Annual rainfall at the nearby Toamasina airport ranges from 3.0-3.5 m per year with the heaviest rainfall between Feb-Apr during the cyclone season. Mean annual temperature is 24°C with minor seasonal fluctuations. Regional topography consists of repeated 100-m hills with up to 50° slopes. Soils are ferralitic red clay interspersed with granite boulders.

Our goals were: (1) to restore native forest to four hectares of land that had been degraded by repeated wildfires resulting from tavy – a form of slash-and-burn agriculture, and (2) to study the ability of native trees to suppress ruderal vegetation, particularly the fern *Dicranopteris linearis*. We selected an applied nucleation design because it was less expensive and because it was conducive to the plot replication we wanted for our experiment.

Implementation and applied nucleation design: This project was implemented by a non-profit organization, Green Again Restoration, on the private land of co-author Jean François Solofoniaina Fidy, the leader of Ambonivato fokontany (small village region). Jean François sought out Green Again to restore his land because he wanted to create a positive example that would inspire other villagers to restore their own family land. This proved an effective strategy. There are now at dozens of restoration projects in Ambonivato fokontany.

Local people were involved in all aspects of the project, from conceptualization to implementation, monitoring, and interpretation. Seeds were harvested from trees on local farms. Nursery weeding and watering were done by crews of single mothers from Ambonivato while their children were in school. Land clearing and tree planting were done by young men from the village, and tree identification tags were made by local women. Measurements and data entry were all done by local villagers. DMH lived in Ambonivato for four years during this project, and his role was limited to education, data proofing, and quality control.

Our site was a four-hectare field on a steep, southeastern-facing slope, ranging in elevation from 30-70 meters above sea level. Local villagers prepared the planting sites by clearing vegetation only in the areas where trees were to be planted (Fig. 1). Surrounding vegetation consisted mainly of a fern (*Dicranopteris linearis*) and traveler's palm (*Ravenala madagascariensis*). Subsequently they planted 160 16-m_2 square tree islands. Each tree island consisted of 25 seedlings of a single tree species planted 1 m apart in a 5 x 5 grid. A total of 4,000 trees were planted. Tree species included 11 native species whose seeds were locally collected and propagated in a nursery. The approximate cost of site prep and tree planting was $1 USD per tree (i.e., about $4000 total, or $1000 per ha).

Outcomes: social and ecological: Our project was planted between June and September 2016. On October 14, a wildfire swept through the site (Fig. 2). We inspected each seedling and developed an index of fire intensity based on the extent of damage to plastic seedling tags, wooden posts, and aluminum plot tags. After several months, we revisited the site and inspected each planting position to look for evidence of seedlings resprouting.

Out of the 4,000 trees planted, 379 (9.5%) survived the wildfire. The percent survival varied among species from 0% to 18% (Fig. 3). Trees on the corners and edges of applied nucleation plantings were exposed to the most intense fire, and survival was lowest for trees planted in those positions. Survival was up to five times greater for trees planted in the island core.

One of the key lessons of this project is that applied nucleation plantings are particularly vulnerable to wildfires because of their greater edge density (e.g., there are more edges per area of forest than in a more continuous plantation). *Dicranopteris* ferns and their thatch formed the matrix between tree islands in our plantings. This thatch was highly flammable, and as a result, tree seedlings planted on the edges of islands sustained greater damage during the wildfire than tree seedlings situated in island cores.

Figure 1: Villagers from Ambonivato establish an applied nucleation planting in a dense fern thicket. Traveller's palm (*Ravenala madagascariensis*) is the large-leaved plant in the back right. Both the fern and the palm are highly flammable. Planting positions are marked with wooden stakes, which were later used to create a standard fire intensity index. Photo by D. M. Hill.

Figure 2: A wildfire that swept through the restoration site in October 2016. It killed 91.5% of planted tree seedlings and revealed a key vulnerability of applied nucleation. Photo by D. M. Hill.

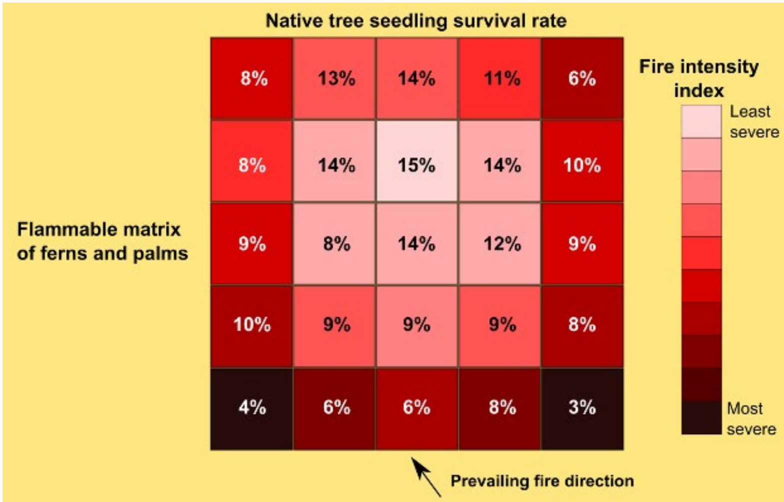

Figure 3: Average tree seedling survival and fire intensity in 160 applied nucleation plantings at our site in eastern Madagascar. The most dangerous seedling positions were the corners and edges of applied nucleation plantings.

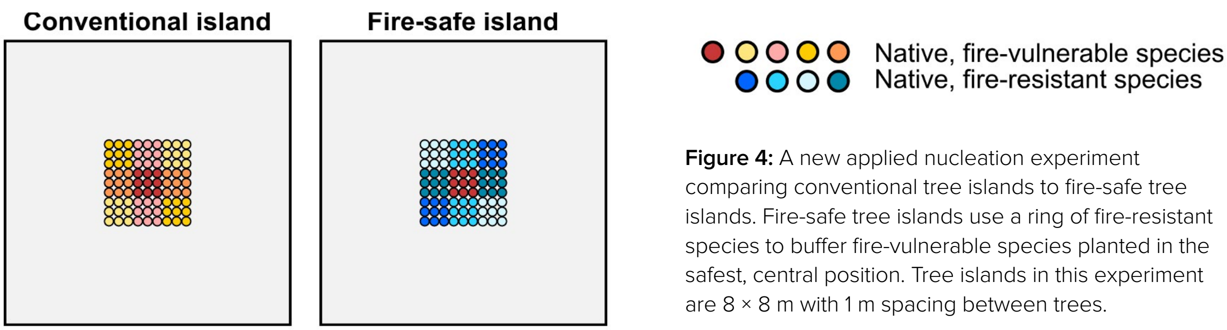

Figure 4: A new applied nucleation experiment comparing conventional tree islands to fire-safe tree islands. Fire-safe tree islands use a ring of fire-resistant species to buffer fire-vulnerable species planted in the safest, central position. Tree islands in this experiment are 8 × 8 m with 1 m spacing between trees.

To correct this problem, we are now testing fire-safe tree islands (Fig. 4). Fire-safe islands have fire-resistant trees planted on the border, where we saw that fire intensity was most severe. Tree species that are sensitive to fire are planted in the island core, where they will be buffered from the hottest temperatures. We have planted more than two dozen sites comparing conventional tree islands to fire-safe islands. We expect that wildfires will demonstrate soon whether fire-safe islands are more resistant to this common disturbance. We also recommend that where wildfire is a risk, practitioners consider maintaining devegetated buffer strips around the entire site (not individual islands) to minimize the risk of losing trees to wildfire.

CASE EXAMPLE 6:

Comparing Three Tree Planting Designs For Atlantic Forest Restoration In Brazil

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[2]Environmental Studies Department, University of California, Santa Cruz, CA 95064, USA.

Context: This nucleation case example consists of a research project established at the Itatinga Experimental Station of Forest Sciences of the University of São Paulo, located in Itatinga-SP, Brazil. The region has a mean annual temperature of 17°C, wet and warm summers, dry and cold winters, annual precipitation of ~1,200 mm and annual water deficit of 20 mm. Soil is characterized as Yellow Distrophic Latossol, with low pH and nutrient content, and sandy texture. Natural vegetation is an ecotone between seasonal semi-deciduous forests (Atlantic Forest) and savanna woodlands (Cerrado), both top hotspots for global conservation priorities. The study site is not legally protected and was covered by a eucalypt monoculture for the past 70 years. We established this experiment to test nucleation effectiveness at operational scales, and using strips (rather than traditional 'islands') to distribute trees over the restoration site.

Implementation and applied nucleation design: Trees were planted in strips (3-4 lines of trees) akin to a plantation style planting, but leaving unplanted strips between the lines to recolonize naturally. This is similar to a strip-cutting logging approach which facilitates natural regeneration and survival and growth of some planted native species (Ashton et al., 1998; Rondon et al., 2009). It has a few potential benefits: like applied nucleation, strip planting should result in reduced costs for planting and maintaining planted seedlings, and it could provide more habitat heterogeneity by providing both planted and unplanted areas. In addition, it presents fewer logistical obstacles for planting and finding seedlings for maintenance, as re-encountering patches of recently-planted tree islands can be challenging in areas with dense pasture grasses (Holl et al., 2020). Moreover, many areas required to be restored under the Brazilian forest code are riparian buffers - strip planting may be well suited to this context. We are not aware, however, of any large-scale experiments to date testing a strip planting approach for tropical forest restoration.

We established a forest restoration study in August 2017 to compare plantation style planting (planting the entire area with trees), applied nucleation (planting patches/islands of trees), and strip planting (planting rows of trees separated by open strips). The study was set up consistent with current forestry practices at a scale that is meaningful to inform on-the-ground restoration efforts. We tested the following treatments: 1) Square islands covering 25% of the area; 2) Square islands covering 50% of the area; 3) Trees planted in strips covering 25% of the area; 4) Trees planted in strips covering 50% of area; and 5) Plantation covering the entire area (Fig. 1, 2). We used 1-ha plots and a randomized block design with five replicates each, totaling 25 ha of experiment. We did not vary the size of the islands, as both Zahawi and Augspurger (2006) and Zahawi et

[4]*The University of São Paulo provided the experimental site, and The Environmental Secretariat of the State of São Paulo and NGO SOS Mata Atlântica provided funding for establishment and longer-term maintenance, respectively. A private company was hired to plant the trees and another company, composed of local people, to maintain them.*

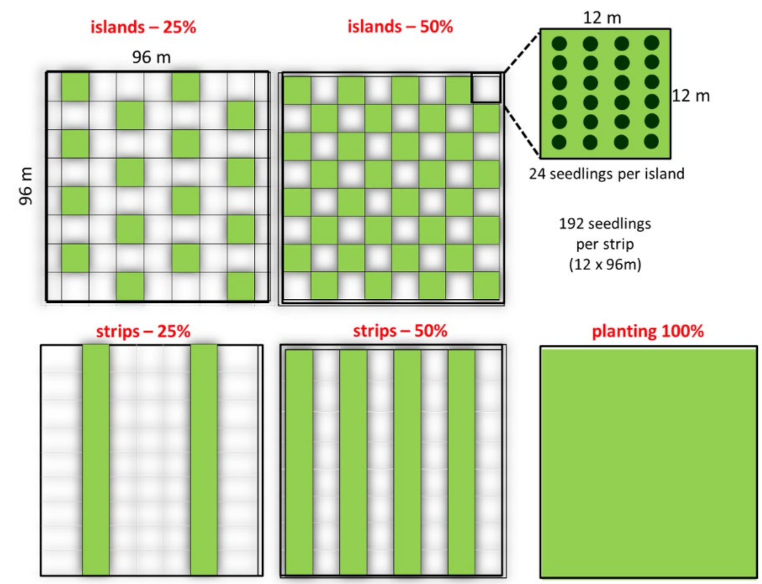

Figure 1: Tree planting treatments tested in the experiment.

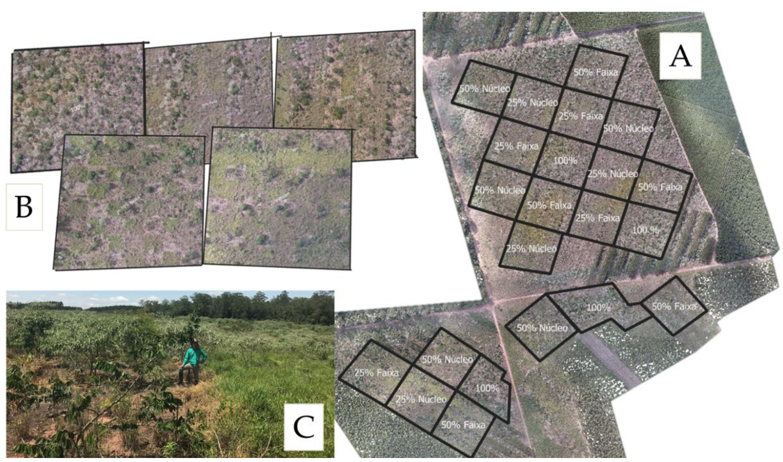

Figure 2: Aerial overview of the experiment (A) and of treatments (B), and the contrast between a planted and non-planted area (C), 1 year after planting.

al. (2013) show that there is a minimum critical island size of ~100 m2 needed to both attract bird seed dispersers and enhance seedling establishment. We used 12 x 12 m islands, four planted lines separated 3m from each other.

We sought to establish a canopy quickly, provide heterogeneity in canopy architecture, and attract seed-dispersing fauna. All planted areas used the same proportions of species: five fast-growing, wide-canopy native tree species and 36 intermediate-growth species (half of them animal-dispersed and half abiotic-dispersed). We selected species that are easy to find in forest nurseries in the region. Priority was given to intermediate-growth species that can attain greater individual size. *Inga vera* was planted at a higher density than other fast-growth, wide-canopy native tree species because it has a remarkable canopy lateral expansion and is a long-lived pioneer. The number of species planted is lower than the more diverse of the Brazilian Atlantic forest restoration projects (Rodrigues et al., 2009), but our focus was on keeping the overall design manageable, and on how the different planting designs facilitate the colonization of other species.

We compared the effects of these planting methods in terms of (1) planted seedling survival and growth, (2) natural regeneration, (3) invasive grass cover, (4) implementation and maintenance costs, and (5) cost-effectiveness for carbon sequestration, biodiversity recovery, and legal compliance with pre-set restoration standards. We have preliminary results, but these are not yet ready for detailed presentation.

Outcomes: social and ecological: Planting operations were much faster and cheaper for establishing planting lines compared to islands, as we used a forestry subsoiler. It is not possible to use a subsoiler for islands because it cannot be relocated in and out of the soil. After three years, seedling performance thus far is similar between treatments. As expected, controlling invasive grasses has been more challenging in both tree nuclei and strips compared to plantation-style plantings. More detailed results are in the process of being analyzed by this team.

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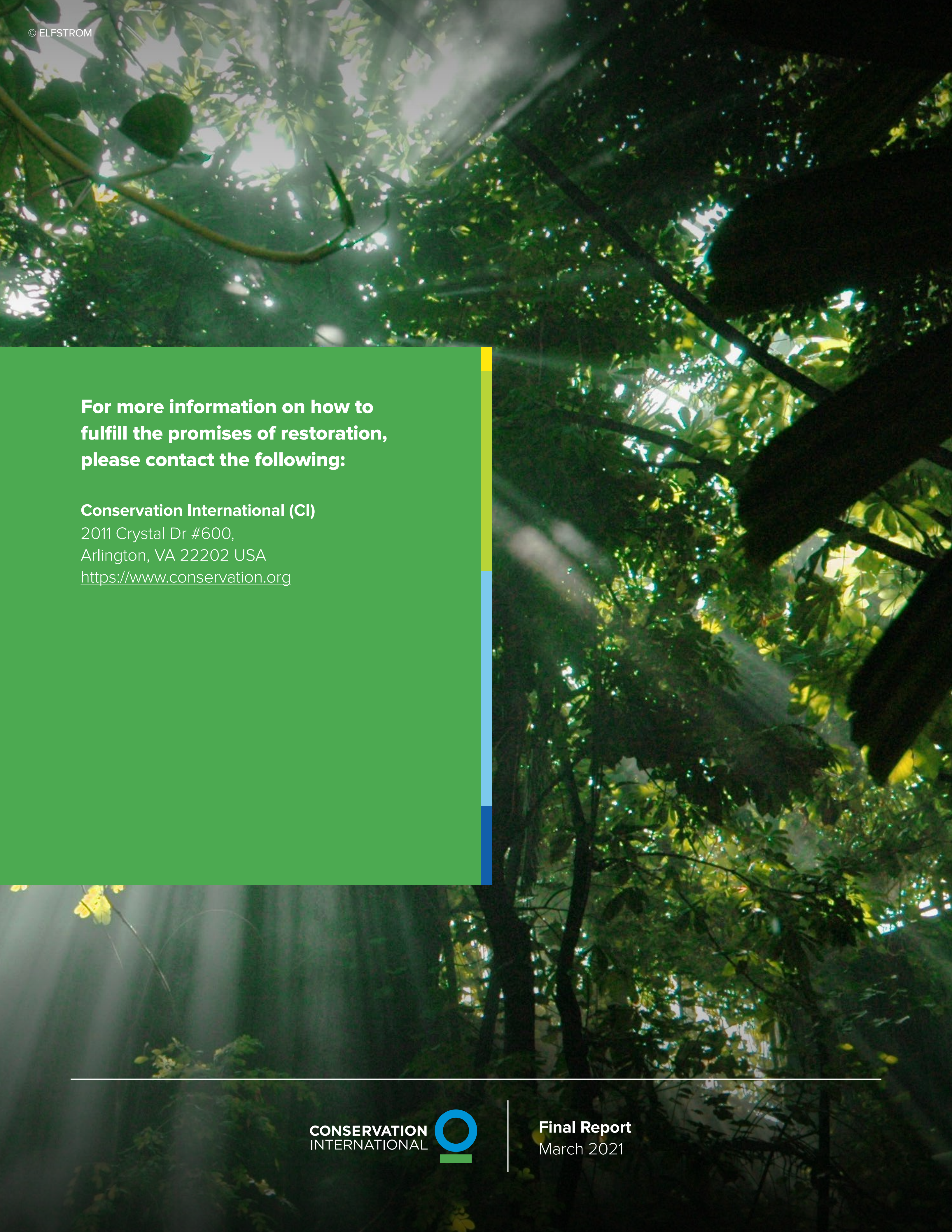

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