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Upscaling ecological restoration by integrating with agriculture

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Title: Upscaling ecological restoration by integrating with agriculture

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Abstract: Transformative change is needed to align common small-scale ecological restoration approaches with expectations to restore millions of hectares of degraded lands globally. Currently, most restoration projects target small areas using costly manual methods that cannot scale to global commitments. Here, we argue that the judicious integration of agricultural practices into ecological restoration offers this opportunity. This transformative process relies on three sequential, interconnected steps: (1) it is critical to ensure that sufficient land is truly available for restoration; (2) loss of agricultural production, income, or land value must be compensated for landholders to choose restoration; and (3) restoring native ecosystems across the promised hundreds of millions of hectares requires methods that are scalable, cheaper, and effective in delivering benefits to nature and people. Large-scale terrestrial restoration will require incorporating agronomic practices in the restoration toolbox in order to go beyond vague, ambitious promises and wishful thinking.

Key words: agroforestry; climate change mitigation; large-scale restoration; reforestation; restoration economics; restoration methods; tree planting

Open Research statement: No data were collected for this study

In a nutshell:

- Current ecological restoration approaches are insufficient to achieve ongoing pledges to restore millions of hectares in coming years.
- We assert that scaling up restoration to meet global initiatives necessitates including agronomic practices amongst the options for restoration methodologies.
- We propose that such integration can increase the land area available for restoration and make restoration at scale more financially and logistically feasible.
- Transforming restoration with judicious integration of agronomic practices is perhaps the only viable option matched to the ambitious scale of restoration commitments.

Introduction

Ecological restoration (*sensu* SER 2004) is rapidly gaining momentum as a central approach to address the most challenging environmental crises of our times, from climate change to the sixth mass extinction. The world is rallying around ambitious pledges, with several multi-million-hectare restoration initiatives, embraced by the United Nations Decade on Ecosystem Restoration (2021-2030). For instance, meeting the Bonn Challenge goal of restoring 350 million hectares of forested landscapes by 2030 would mean restoring ~20% of agricultural land globally in less than a decade.

Stakeholders from myriad sectors are engaged in the global restoration movement, and restoration programs have never been so well resourced (Lamont *et al.* 2023). Since most of the investments needed to restore ecosystems at the promised scale are still to be made (Mirzabaev and Wuepper 2023) and restoration processes have not started yet in the vast majority of targeted areas (Fagan *et al.* 2020), there is still a window of opportunity to develop restoration approaches that optimize each dollar invested and magnify benefits for nature and people (Hua *et al.* 2022). In short, it is critical to find ways to rapidly upscale restoration.

Challenges for upscaling restoration

The attempts to improve the cost-effectiveness of global restoration commitments have been mostly focused on spatial prioritization analyses, which have often explored the restoration benefits for carbon accumulation, biodiversity conservation, water quality, and habitat connectivity across global (Strassburg *et al.* 2020) to regional scales (Gilby *et al.* 2020, Singh *et al.* 2019). Few of these studies have included restoration implementation and maintenance costs, potential revenues from restoration activities, and lost opportunity costs from previous land uses, which limits the applicability of such spatial analysis. In addition, such "remote" planning of restoration initiatives has systematically failed to incorporate social issues, a cornerstone limitation for an activity that relies on engagement and participation of local people (Erbaugh *et al.* 2020, Fleischman *et al.* 2022).

In addition to deciding where to restore, it is critical to consider how to restore ecosystems, as different methods have varied implementation and maintenance costs, as well differential outcomes in terms of ecosystem goods and services, which results in context-specific socio-economic feasibilities (Brancalion *et al.* 2019, Gann *et al.* 2019). Unfortunately, most current ecological restoration is still implemented at small sites using costly manual methods that cannot scale to global commitments. Examples of these "boutique" (i.e., creative and sophisticated, but unviable at scale) restoration strategies abound. Techniques such as moving small quantities of leaf litter from remnant forests, installing bird perches or encrusting native seeds in fruit pulp to attract fauna, and hand weeding undesirable species (e.g., Bahia *et al.* 2023, Humphries *et al.* 2021, Silva *et al.* 2020) are alluring but are not feasible economically or socially beyond a few hectares.

Although different restoration methods and operational procedures rarely have been rigorously compared at scale at multiple sites in the same region (see Florido *et al.* 2022, Holl *et al.* 2014 , Raupp *et al.* 2020, Knight and Overbeck 2021 for a few examples at experimental conditions for some ecosystems), restoration practitioners and companies are well aware of the marked cost differences and have often made empirical evaluations to improve the cost-efficiency of their projects (Panel 1). Transformative change is needed to align the scale of restoration expectations with reality. Judicious integration of agricultural practices into ecological restoration offers this opportunity.

Integrating agriculture with restoration

Although controversial given the business-as-usual ecological restoration mindset and the enormous environmental footprint agriculture has had across the globe, integrating agricultural practices (including forestry and livestock production) is a key transformation in the emerging and rapidly evolving field of restoration ecology. In the late 20th century, restoration ecology came into its own as an academic discipline, strongly rooted in theories of ecological succession. Ecological restoration as a solution to environmental degradation emerged from small-scale ecological experiments, based on the assumption that human activities represent disturbances to be avoided and repaired. Recent criticism of the predominant ecological focus of restoration has grown among practitioners and scientists alike, and human dimensions have been progressively incorporated (Tedesco *et al.* 2023). The 'call to action' of the 2023 World Conference on Ecological Restoration highlights the need to both engage local people and marginalized social groups, and to upscale restoration initiatives across the planet (SER 2023).

Ecological restoration is now a multidisciplinary field and is part of a continuum of restorative practices with nuanced boundaries, multiple objectives, and greater integration with human-dominated land uses (Gann *et al.* 2019). Three observations highlight the need to accelerate restoration by incorporating agricultural practices. First, most of the regenerating native forest area is not the outcome of a planned ecological restoration initiative; rather, new forests have re-grown spontaneously on previously-farmed lands as consequence of major socioeconomic shifts in agriculture (Chazdon *et al.* 2020). As predicted by forest transition theory and validated in numerous studies, forest cover increases have generally relied on governance, secure land tenure, livelihood issues, and trade agreements of agricultural products (Rudel 2023). Second, the primary global restoration commitments (e.g., the Bonn Challenge and the UN Decade on Ecosystem Restoration) embrace the framing of a continuum of restorative activities ranging from a focus on repairing ecosystem functions within working landscapes to fully recovering native ecosystems (Gann *et al.* 2019). Finally, many organizations largely plant profitable commercial or utilitarian species rather than native species that maximize biodiversity conservation (Martin *et al.* 2021).

This transformation of restoration arguably started by recognizing the vital connection between restoration and land-use decisions by landholders, who are heavily focused on subsistence and financial returns, rather than on ecological outcomes or broader societal benefits. A major contemporary challenge is to shift restoration from an activity that emerges as socioeconomic side effects of land use changes or is mandatory for legal compliance into a competitive and complementary land use. This requires the recognition that land is a primary limiting restoration resource, and that restoration will only succeed and expand if well integrated with other land uses that maximize nature's contributions to people.

Expanding the land and revenue for restoration

It is critical to ensure that sufficient land is truly available for restoration. Different approaches to designate lands for restoration can be employed individually or in combination to achieve this end, such as: (1) establishing legislation and policies to oblige the protection and restoration of native ecosystems in sensitive ecological areas within agricultural landscapes (e.g., along waterways or wetlands, habitat for threatened species) (Cole *et al.* 2020); (2) providing financial compensation (e.g., payments for ecosystem services schemes) to landholders for forgone agricultural production in areas targeted for restoration; and (3) improving land use planning to optimize agricultural production on more fertile land and releasing marginal agricultural land for restoration (Cook-Patton *et al.* 2020). In these contexts, production and restoration areas are integrated across the landscape but occupy different locations, creating interconnected mosaics that may synergistically maximize both production, through increased land use efficiency and enhancement of pollination and pest control services (López-Cubillos *et al.* 2023), and environmental benefits, through habitat creation for wildlife and improved ecosystem functions like soil protection (Teng *et al.* 2019). The loss of agricultural production, income, or land value must be compensated for landholders to choose restoration (Richards *et al.* 2020), in order to avoid much of the "abandoned" and "restored" land being re-cleared, as has occurred globally in recent decades (Crawford *et al.* 2022).

Another promising approach is to obtain revenues from restoration and increase its competitiveness as an alternative land use, which would financially compensate the replacement of less productive agropastoral land uses by restored ecosystems. Alternatives include the generation of carbon credits (Dybala *et al.* 2019), and the production of timber and non-timber forest products, along with value added processing (Harrison *et al.* 2020). Finally, agricultural production and restoration can share the same location, by integrating restorative and agronomic practices into multipurpose land use schemes (Hart *et al.* 2023). For instance, producing crops in successional agroforestry models (Andrade *et al.* 2020) and farmer managed natural regeneration (Chomba *et al.* 2020); raising cattle in silvopastoral systems (Calle 2020); growing coffee, cocoa, and other woody crops in shaded systems (Hart *et al.* 2023); and intercropping commercial trees with native species (Brancalion *et al.* 2020) to restore ecosystem functions while providing income to landowners. These systems offer a "middle way" solution towards a transition to ecological restoration.

Enhancing the operational efficiency of restoration methods

Restoring native ecosystems across the promised hundreds of millions of hectares requires methods that are scalable, cheap, and effective in delivering benefits to nature and people. Whereas other human activities benefit from increasing technological sophistication, many restoration projects still rely on tedious processes. The rise of agriculture as the dominant land use on the planet was only possible because of continuous development of technologies such as machines, herbicides, irrigation, and synthetic fertilizers. Currently, many of the improvements in restoration operational efficiency has come from trial-and-error processes to adapt existing agricultural technologies to the field of restoration. Here, we present five examples, covering different steps of a restoration process.

- ***Seed and seedling* production:** Commonly-used manual seed collection, seedling propagation, and planting techniques hinder restoration-project scaling. Expanding this plant-production supply chain will require more consistent demand for seeds and seedlings, facilitated by government price supports typically used to ensure consistent agricultural production (NAS 2023). Already-existing agricultural techniques such as seed orchards and appropriate seed processing equipment should be expanded to scale up seed production. Technologies developed over several decades for industrial-scale eucalypt and pine plantations have been adapted to annually produce nearly 40 million seedlings of over 100 native tree species for Brazilian Atlantic forest restoration while employing many workers at different stages of the process (Silva *et al.* 2017; Box 1). The sophisticated, highly automatized infrastructure of these modern nurseries producing native tree seedlings (Figure 2A) contrasts with the manual, laborious procedures they still employ to overcome seed dormancy, a process that can also be scaled. For example, mechanized seed scarification increased germination 64% over manual scarification for two native midwestern U.S. legumes and is much more practical for the large quantities of seeds needed for restoration (Olszewski *et al.* 2010).

- ***Soil preparation*****:** Agricultural methods can be integrated to overcome common barriers to plant survival and growth in restoration, namely high soil compaction and low fertility. As restoration of terrestrial ecosystems has often occurred in degraded soils, soil amelioration is a central activity for restoration success. All machinery used today in large-scale restoration has come from agriculture. For instance, subsoilers used in commercial forestry have been largely used to decompact the soil of planting areas up to 1-m depth, so as to create favorable conditions for the root system of native trees in forest restoration (Löf *et al.* 2012). Another opportunity for integration comes from the use of the large amounts of organic wastes generated by agricultural systems (e.g., coffee pulp, empty oil palm fruits), which can be applied to restoration sites to increase soil nutrient and water availability. For example, applying coffee pulp to a forest restoration site in Costa Rica increased mean woody basal area 30-fold compared to the control treatment (Figure 2B)(Cole and Zahawi 2021).

- ***Sowing seeds and planting seedlings*****:** Various examples show that enlisting agricultural technologies can be a game changer in sowing seeds and planting seedlings at large scales. Soybean-sowing machines have been adapted to inexpensively plant native tree seeds at scale in central Brazil (Durigan *et al.* 2013). Similarly, vegetable planting machines have been modified for establishing grass plugs to restore grasslands in California (Figure 2C). A number of seed enhancement technologies widely used in agriculture, such as seed priming and coating, show promise to increase germination and synchronize germination timing to rainfall conditions, particularly in semi-arid systems (Pedrini *et al.* 2020). These seed enhancement technologies have been used recently to improve the use of drones to spread native seeds over restored areas (Castro *et al.* 2023), which expedites large-scale restoration in remote areas.

- ***Reducing weed competition*****:** Competition with invasive, non-native species is a central barrier for restoration success (Weidlich *et al.* 2020). Judicious use of herbicides developed for agriculture can be a cost-effective tool for controlling invasive species at the outset of restoration to facilitate native plant establishment. For example, using non-chemical methods were at least 10 times more expensive than herbicide to control non-native grass species in California grassland restoration (Holl *et al.* 2014). Spraying technologies have advanced rapidly in recent years with the growing use of selective products and precision application approaches and drones that minimize use per area. We note, however, that herbicide use should be part of a thoughtful integrated weed management plan that considers local constraints and cost-risk trade-offs, and should be used only in the first years of initiating a restoration project with more targeted approaches used for ongoing maintenance. In addition, the environmental impacts of herbicides have primarily been tested in agricultural systems, so it is important to evaluate their effects in the restoration context, particularly the potential long-term effects on native biodiversity.

Job impacts of upscaling restoration

The needed transformation of restoration practice will potentially require less labor per hectare for certain tasks previously done manually (e.g., weeding, planting). But the impacts of technology intensification on jobs observed in agriculture (Brondizio *et al.* 2023) may not be as high in restoration, as it is still an emerging activity with many fewer people employed, and it is often done on marginal lands with uneven terrain and diverse plantings that constrain intense mechanization. Even so, there are critical trade-offs to be considered between restoration scalability and per hectare employment, which highlights the need for context-dependent solutions.

In regions with a predominance of small landholders who rely on land for income, food, and other resources, and/or restoration initiatives have the central goal of creating job opportunities for local people (e.g., the Working for Water program in South Africa), traditional, labor-intensive restoration approaches are likely more appropriate to maximize social outcomes regardless of their potentially lower operational efficiency and higher costs. In these conditions, government and NGO-led restoration initiatives should even go beyond the consideration of the impacts on jobs and reflect more broadly on social conditions and equity (Edwards *et al.* 2021).

Conversely, expanding restoration as an entrepreneurial activity, on large properties and level terrain, and for mitigating broad scale environmental impacts, relies on the reduction of costs and improvements of operational efficiency, which will inevitably increase the pressure for greater labor productivity. In regions with lower availability of rural labor, such reduction of per hectare employment can be critical to make restoration projects feasible. Moreover, despite the lower local demand on less qualified jobs, upscaling ecological restoration by integrating with agriculture may increase the total number and qualification of jobs created (Raes *et al.* 2021). For instance, only one fourth of the restoration labor force in Brazil is employed in planting and maintenance; the rest are concentrated in activities (e.g., seed and seedling production, project design, monitoring) that benefit from adopting technologies to scale up restoration (Brancalion *et al.* 2022).

The way forward

Integrating agriculture and restoration requires a critical consideration of the pros, cons, and lessons learned from past successes and failures of agricultural practices to adapt them to the novel conditions of restoration and minimize unintended ecological and social consequences. Although the massive expansion of agriculture came at a cost to ecosystems, biodiversity, and associated ecosystem services, the thoughtful use of agricultural technologies in the opposite direction, namely to restore these features on agropastoral lands, holds potential to replenish natural capital within a timeframe needed to mitigate major environmental losses. Some agricultural technologies should not be adopted because of their environmental and social impacts, which have the potential to be greater in restored lands due to higher levels of biodiversity and use by traditional and indigenous communities. Alternatively, some technologies can be tailored to a restoration context or combined with traditional restoration approaches to increase effectiveness and reduce costs. To reiterate, we are not recommending a one-size-fits all approach. There are many trade-offs related to social and environmental impacts of technology adoption that will need to be considered in designing restoration approaches, along with ecosystem type, funding available, project scale and goals, land terrain, and other factors.

Transforming ecological restoration with judicious integration of agronomic practices is perhaps the only viable option matched to the ambitious scale of restoration commitments. The scale of restoration proposals demands that practitioners expand their toolbox. In this context, international organizations supporting restoration have to move beyond picturesque small-budget projects to support the co-production of knowledge, technology transfer, and capacity building for scalable restoration approaches. Moreover, we reiterate the frequent calls to directly compare restoration approaches in the same system and report the relative costs of the different restoration approaches publicly, as this information is essential to incorporate information on cost-effectiveness in the decision-making processes (Kimball *et al.* 2015, Knight and Overbeck 2021). The obvious risks to adopting agricultural practices in restoration contexts require navigating complex ethical dilemmas and considerations of social equity issues. But these risks are likely more manageable and acceptable than the imminent impacts of catastrophic climate change, biodiversity loss, and social inequality. Large-scale restoration must go beyond vague ambitious promises and wishful thinking.

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Panel 1: Differences in costs and operational efficiency of traditional versus scalable approaches to restore tropical forests in Brazil. In the past decade, forestry methodologies employed in commercial eucalypt production have been applied to large-scale forest restoration, revolutionizing the field by markedly reducing costs and increasing operational yields (Table 1). Early in the restoration of the Atlantic Forest, seedlings were produced in plastic bags filled with soil, which resulted in heavy, high-volume seedlings that were difficult to manage in nurseries, increased transport costs, and reduced planting yield (Table 1). This scenario was drastically transformed by the introduction of plastic tubes and commercial forestry substrate as alternatives (Table 1) and, more recently, by the replacement of plastic tubes by paper pots (Figure 1A), growth substrate wrapped in biodegradable paper, which resolved the need to transport the tubes back to the nursery after planting. For soil preparation, the use of manual posthole diggers, which has a low yield and often produces holes of low quality for planting in restoration contexts, have been replaced by earth auger machines (Figure 1B) in areas with uneven terrain and subsoilers (Figure 1C) in areas with level ground that can be fully mechanized. These changes have resulted in substantial increases in productivity (Table 1). The use of smaller seedlings produced in plastic tubes or paper pots allows people to plant while standing using pottiputki planters (Figure 1D), which increases yield, reduces costs (Table 1), and improves ergonomics. Finally, the use of herbicides to kill weeds rather than repeated pruning has reduced the number and costs of maintenance interventions (Table 1). Additional advantages of herbicide spraying include a nine-fold increase in seedling growth, greater regeneration of native woody plants (Florido *et al.* 2022), and lower risks of fires and cattle invasion. Together, these novel technologies have allowed a 2-3-fold reduction of per seedling costs and greatly increased the operational efficiency of restoration projects.

Figure 1: Examples of scalable approaches to restore tropical forests.

Table 1: Costs (in US$) and yields of nursery-grown seedlings and different restoration operational procedures in southeast Brazil. Values represent the mean ± 1 standard deviation of estimated costs and yields informed by two restoration companies for a standard restoration project in the region of the Atlantic Forest where they operate (*i.e.*, values reflect different local restoration conditions and labor costs). Both companies considered a 3 × 2 m spacing (*i.e.*, 1,666 seedlings per hectare) and did not include replanting, fertilization, and leafcutter ant control, as those costs are similar across restoration methods.

Figure 2. Examples of agricultural approaches integrated with ecological restoration. (**A**) A forest nursery in São Paulo, Brazil producing four million native tree seedlings per year, using production technology largely adapted from the eucalypt industry (Photo credit: Paulo Molin). (**B**) Increased performance of tropical forest regeneration in Costa Rica resulted from the addition of coffee pulp residues on degraded soils (back image), contrasting with the near absent regeneration when no residue was used (front image) (Photo credit: Rebecca Cole). (**C**) Vegetable planting

machines used to plant local grass species in a restoration project in California, USA (Photo credit: Jonathan Pilch).

Figure 1: Examples of scalable approaches to restore tropical forests.

568x379mm (300 x 300 DPI)

Figure 1: Examples of scalable approaches to restore tropical forests.

1151x863mm (72 x 72 DPI)

Figure 1: Examples of scalable approaches to restore tropical forests.

1422x1066mm (72 x 72 DPI)

Figure 2. Examples of agricultural approaches integrated with ecological restoration. (A) A forest nursery in São Paulo, Brazil producing four million native tree seedlings per year, using production technology largely adapted from the eucalypt industry (Photo credit: Paulo Molin). (B) Increased performance of tropical forest regeneration in Costa Rica resulted from the addition of coffee pulp residues on degraded soils (back image), contrasting with the near absent regeneration when no residue was used (front image) (Photo credit: Rebecca Cole). (C) Vegetable planting machines used to plant local grass species in a restoration project in California, USA (Photo credit: Jonathan Pilch).

197x338mm (300 x 300 DPI)

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685x914mm (72 x 72 DPI)

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231x282mm (72 x 72 DPI)

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196x338mm (72 x 72 DPI)