One Earth

Review

Assessing innovations for upscaling forest landscape restoration

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SUMMARY

There is an increasing urgency to implement large-scale ecosystem restoration to mitigate the biodiversity and climate crises. These efforts must be scaled up to counteract the widespread degradation of the world's forests, although restoration costs can often limit their application. Thus, there is a pressing need to identify cost-effective approaches that catalyze landscape-scale ecological recovery. Here, we highlight seven assisted restoration innovations with demonstrated local-scale results that, once upscaled, hold promise to rapidly regenerate forests. We comprehensively assessed how each approach facilitated forest, woodland, and/or mangrove recovery across 143 studies. Our results reveal techniques with a marked ability to catalyze vegetation recovery compared to "business-as-usual" approaches. However, the context-dependent cost-benefit ratio and feasibility of applying particular approaches requires careful consideration. Our assessment emphasizes that we already have many of the tools necessary to drive the terrestrial restoration movement forward. It is time to implement and assess their efficacy at scale.

LEVERAGING COST-EFFECTIVE ECOLOGICAL TOOLS TO SCALE UP GLOBAL RESTORATION

Humans have heavily modified the world's ecosystems, and an estimated three-quarters of terrestrial biomes have been either degraded or converted to alternate uses.[1] The field of restoration ecology was formalized to address this challenge[2] and has been referred to as an "acid test" of ecological theory, as our ability to design approaches that recover ecosystem function depends on how well we understand ecological processes in the first place.[3] In recent years, there has been an outpouring of support toward the upscaling of global forest restoration efforts in order to mitigate the combined threats of biodiversity loss and climate change.[4] This global movement is promoted by the 2021–2030 UN Decade on Ecosystem Restoration, which highlights the need to increase capacity building and knowledge sharing across Indigenous, traditional, local, and scientific communities to detail ecosystem restoration best practices (www.decadeonrestoration.org/strategy). However, translating this knowledge into practice at larger scales remains a critical logistical challenge,[5,6] and despite ambitious global forest landscape restoration targets, funding to meet these goals falls short by over $US300 billion annually.[7] The general lack and inflexibility of policy and governance frameworks related to restoration can also present challenges to meeting these goals.[8]

A series of economic challenges must be overcome to make widespread ecosystem restoration a reality: (1) restoration must become an economically viable use of land and/or legally mandated to incentivize the transition from conventional land uses[9]; (2) innovative restoration approaches must be identified that can make landscape-scale interventions cost-effective[10]; and (3) restored ecosystems must be an economically sustainable option for local communities so that they persist in the long term.[11] To make restoration an attractive land use (challenge 1), a wide range of financial mechanisms must be leveraged,[9] and restoration should target lands with lower agricultural productivity.[12] To increase restoration permanence (challenge 3), we must address widespread patterns of forest ephemerality.[11] For example, naturally regenerated forests typically persist for less than a decade in the Neotropics.[13,14] Refining finance

Table 1. Descriptions of the seven innovations for assisted forest restoration evaluated, their business-as-usual approach (i.e., control), and the number of relevant studies on each[a]

Innovation	Description	Business-as-usual approach (i.e., control)	No. studies evaluated
Mixed plantings	increasing taxonomic/functional diversity of initial restoration plantings with native species	monoculture plantations	49
Economic species	including fast-growing economic species (either exotic or native) in initial plantings with the intention of harvesting them in the short term	plantations using only native species	10
Spatially patterned planting	using approaches such as applied nucleation (i.e., planting trees/vegetation in patches) or other patterns to establish clusters of plant species	plantation-style forestry	12
Alternative revegetation	using direct seeding or vegetative propagation (i.e., stakes) instead of tree seedlings	planting tree seedlings	20
Soil microbiome	adding live soil or live spores to planted tree seeds or seedlings	no live soil or live spores added	15
Biowaste	integrating agricultural waste, effluent/sewage, or compost	no biowaste added	22
Biochar	integrating biochar (i.e., charcoal produced by pyrolysis) as a soil amendment	no biochar added	16

See Table S1 for the full list of studies evaluated.
[a]Relevant studies on each innovation that had suitable controls to which to compare vegetation recovery outcomes, and measured relevant recovery indicators (above- and/or below-ground biomass/carbon, tree growth/survival, plant diversity, or forest structure).

mechanisms to value the contribution of secondary forests to mitigating climate change and preventing biodiversity loss[15] and prioritizing community-led initiatives[16] could help to avoid this dynamic and address challenge 1. To bridge responses to challenges 1 and 3, we must determine how restoration approaches can be scaled up (challenge 2) in a way that is as ecologically sound and cost-effective as possible and also increase the chance that restoration persists by directly benefiting local communities.

Ecosystem restoration can include a vast array of interventions, ranging from the conservation of protected land to the assisted promotion of biodiversity within managed landscapes. Identifying the appropriate restoration intervention, or mix of interventions, to enhance biodiversity in a specific region is a key challenge.[17] In many cases, natural regeneration represents a scalable approach to enhance terrestrial carbon capture[18] and recover plant biodiversity.[19] By removing the drivers of degradation, this approach can allow forests to cost-effectively regenerate on their own.[20] However, depleted soils or invasive species often present barriers to the natural recovery of degraded lands, subsequently requiring assisted restoration interventions (*sensu* Chazdon et al., 2021)[21] when certain elements of the ecological community are slow to recover.[22,23] For forest restoration, this most commonly means planting trees.[24,25] Unfortunately, the costs associated with assisted restoration often limit its application.[26] It is necessary to identify cost-effective solutions for assisted ecosystem restoration practices to achieve these solutions at scale. However, it is also important to highlight that there are various other social, ecological, cultural, spiritual, or political values of nature that may be equally, if not more, important than the economic values in different contexts.[10,22,27] Recognizing that there can be inequality in the distribution of costs as well as benefits, we find there is a need for careful assessment of the effects of different restoration approaches both on nature and all relevant stakeholders. With limited data about the true benefits and costs of project implementation and maintenance over time, identifying the most practical strategies given local conditions remains a key challenge.[28,29]

To identify potentially cost-effective approaches for upscaling global forest restoration efforts, we systematically reviewed and quantitatively assessed the ecological outcomes of seven emerging low-tech assisted restoration techniques (hereafter, innovations), that have demonstrated local-scale results and hold promise for landscape-scale implementation in areas that are slow to recover naturally (Table 1). In defining cost-effectiveness we took a broad view, assessing innovations that had lower relative costs per hectare of application and/or led to higher benefits to costs per hectare, as these goals are not mutually exclusive and the ideal approach depends on the context and resources of a given project.[30] We focused our review on innovations that have facilitated forest, woodland, and/or mangrove recovery while also (1) decreasing costs of restoration implementation, (2) offsetting costs of initial interventions, (3) integrating underutilized resources (e.g., biowaste) into the restoration economy, or (4) restoring natural processes more efficiently (Table 1). To assess the effectiveness of these approaches, we compared vegetation recovery outcomes (i.e., recovery of vegetation biomass/carbon, diversity, dynamics, or structure) and implementation costs to "business-as-usual" approaches used in the region (e.g., standard approaches such as plantation forestry). In doing so, we identify the potential benefits of integrating these approaches into restoration practice and highlight the importance of community engagement and knowledge sharing to refine the suitability of restoration interventions for local contexts and of expanding assessments of restoration costs and efficacy at scale.

THE POWER OF INNOVATIONS TO IMPROVE ASSISTED RESTORATION OUTCOMES

Focal innovations

We identified seven restoration innovations as potential approaches that can improve ecological outcomes in a cost-effective manner. To select these innovations, we held a knowledge co-creation workshop on restoration innovation in June 2022 that was attended in-person and remotely by restoration practitioners and researchers working in the field, primarily in tropical Latin America, but with experience in tropical and temperate forests in the Americas, Asia, Africa, and Europe. This was followed by a written comment period where authors synthesized the workshop outcomes, consulted with additional colleagues working in the field, and used knowledge from the ecological literature to refine a final list of assisted forest restoration innovations. These included high-diversity mixed plantings of native species, including fast growing economic species (exotic or native) in plantings; spatially patterned planting (e.g., applied nucleation); alternative revegetation methods (i.e., direct seeding or using plant cuttings/stakes in place of seedlings); soil microbiome amendment; biochar addition; and biowaste addition (Table 1). We recognize that this list is not exhaustive and encourage the development and testing of other restoration innovations that enhance scalability. Still, these represent common approaches that have been explored within the scientific literature as cost-effective options to potentially scale up assisted restoration initiatives, focused on bolstering ecological outcomes. Below, we describe each innovation and its subtype(s), and how we systematically assessed the benefits, implementation costs, and limitations of each compared to business-as-usual approaches (i.e., controls noted in Table 1).

Mixed plantings

A straightforward way to improve assisted forest restoration outcomes when planting trees can simply be to include more species, especially mixes of species with a diversity of traits. Mixed plantations of native tropical tree species are generally more resilient to disturbance than monocultures and can be less susceptible to pathogens and pests, providing a suite of ecosystem function and services (e.g., biodiversity conservation, water security) beyond timber and fiber.[31] Furthermore, mixed-species plantations accumulate biomass more rapidly in many cases,[32,33] in addition to providing long-term canopy cover. This is in contrast to monospecific plantations, which typically comprise fast-growing, short-lived species.[31]

Economic species. The inclusion of economic (i.e., commercially valuable) species in assisted restoration is an attractive way to promote regeneration and provide income to landholders. Exotic, yet non-invasive, timber species are typically avoided when designing native forest restorations, but recent examples demonstrate that carefully integrating these species can improve outcomes. For example, planting exotic economically valuable timber species that are already widely used in the region alongside native tree species, then harvesting and selling the exotic species, can offset the costs of reforestation after accounting for logging and transport costs,[34] with only a slight decrease in the above-ground biomass of native tree species and no impacts on the species richness of naturally recruiting species.[35]

Spatially patterned planting

Forestry row planting techniques are the default for many assisted forest restoration projects, resulting in the creation of spatially homogeneous tree plantations that do not represent the complexity of natural forests. Spatially patterned restoration, in which plants are distributed in clusters (i.e., applied nucleation) or strips rather than throughout a restoration site, can be a more cost-effective approach that promotes the regeneration of a more heterogeneous habitat structure across landscapes.[36] In tropical forests that are slow to regenerate, applied nucleation, alternating strips of trees with unplanted areas,[36] and plantation forestry can recover structure and function as well as plant and animal diversity at equivalent rates,[37,38] with the costs of spatially patterned planting scaled to the area planted and typically one-third to one-half lower.[39,40]

Alternative revegetation

Seedlings are used overwhelmingly in assisted forest restoration efforts, despite many projects demonstrating that two subtypes of this approach—direct seeding or planting cuttings/stakes (i.e., vegetative propagation)—can be more cost-effective and easier to use in certain contexts. Directly seeding tree species with mechanized broadcasting has been effective at restoring 90 tree species from seed in large sites (up to 50 ha) in tropical wet forests in the Brazilian Amazon,[41,42] as well as forests in Laos,[43] and direct seeding costs are less than half that of planting seedlings in some regions of Brazil.[44] Alternatively, certain tree species planted as stakes can accumulate biomass and develop canopy cover much more rapidly than seedlings[45–47] for as little as one-third of the cost.[46]

Soil microbiome

The use of microbiome transplants has long been understood for agricultural symbionts[48] and some forestry systems,[49] yet application in a restoration context is relatively new. Remarkable success of soil microbiome restoration has been observed in extremely challenging habitats, including restoration of heathlands,[50] reintroduction of native grasslands on degraded mine sites,[51] and reestablishment of late-successional American prairie grass species.[52] Additionally, tree growth rates can be strongly tied to their mycorrhizal symbionts,[53] and growth rates of certain tree species have responded positively when inoculated in the field using two subtype approaches: planting seedlings (i.e., tree planting)[54] or direct seeding.[55] Beyond these specific cases, multiple syntheses have shown that the reintroduction of native microbiota can accelerate plant biomass recovery across a wide range of ecosystems.[54,56]

Biowaste

Multiple biowaste subtypes (agricultural, compost, effluent/sewage) have shown promise in catalyzing assisted restoration outcomes, and substantial quantities of these wastes have limited to no alternative uses or market value, presenting an underutilized resource for restoration. In agricultural systems, billions of tons of waste product such as coffee pulp, citrus peels, sugarcane bagasse, and empty oil palm fruit are produced in countries around the world.[57,58] Applying these nutrient-rich agricultural by-products has shown substantial promise to amend degraded soils and speed natural regeneration.[59–61]

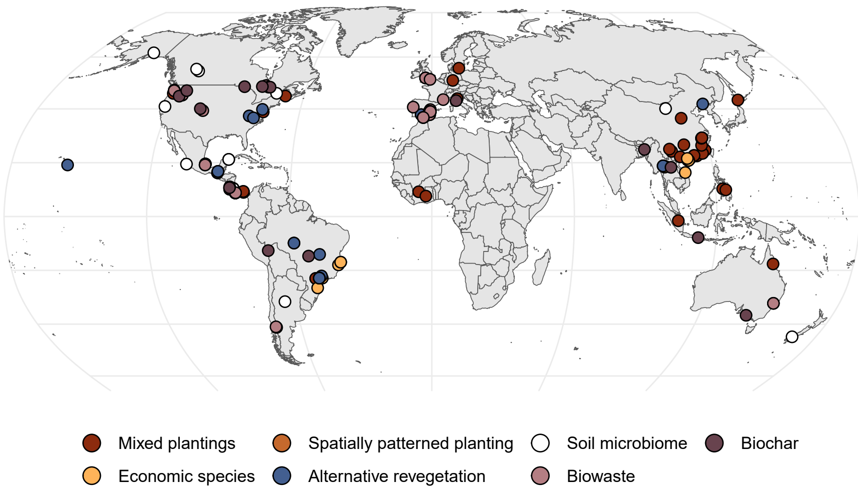

Figure 1. Locations of each study, separated by innovation evaluated (N = 143 studies)

Composts and effluent/sewage have also improved vegetation recovery outcomes in restoration projects, and because effluent/sewage is ubiquitous and could be used more efficiently,[62] repurposing it for restoration could represent a "win-win" for industry and conservation. Indeed, effluent biosolids have been particularly effective at speeding the recovery of carbon stocks post-mining activities[63] and fires.[64]

Biochar

Another promising avenue is using biochar (i.e., charcoal produced by pyrolysis) as a soil amendment in assisted forest restoration.[65] In many contexts, biochars have been demonstrated to increase crop yields,[66,67] as their addition can stimulate processes such as mycorrhizal colonization in nutrient-poor soils and increase factors such as soil alkalinity, thus increasing phosphorus, potassium, and nitrogen availability.[66,68] Despite the challenges of sourcing and ensuring that a suitable biochar is applied in each context, a global meta-analysis showed that tree biomass increased an average of 41% with biochar addition, with tree growth in boreal and tropical ecosystems increasing the most dramatically.[65]

Evaluating the influence of innovations on vegetation recovery

For each innovation, we systematically reviewed the literature to summarize its impact on assisted forest recovery, with the goal of restoring natural ecosystems, in terms of woody vegetation recovery outcomes (i.e., indicators; see Figure S1 and experimental procedures for more details): above- and below-ground biomass/carbon accumulation, tree growth/survival, plant diversity, and/or forest structure (i.e., woody vegetation cover, stem density, basal area). Our initial searches identified 6,456 studies, of which we fully reviewed all that met our inclusion criteria (field studies conducted in biomes dominated by woody vegetation that included empirical recovery data or data on implementation costs; N = 342 studies within scope). We extracted implementation costs per hectare from all studies (N = 17) where they were included. Then, we extracted vegetation recovery outcomes (N = 239 observations) from all studies that compared a given innovation to business-as-usual approaches (N = 143; Figure 1; Table S1).

To determine how vegetation recovery outcomes (i.e., indicators) compared between each innovation and its respective business-as-usual approach (i.e., control; see Table 1), we used the results of pairwise statistical comparisons between the treatments within each study. In some cases, more than one recovery outcome was extracted from a single study, as many studies measured the recovery of more than one vegetation recovery indicator (Figure S1). For each indicator × innovation combination we determined whether vegetation recovery outcomes at the end of each study were lower or higher ($p \leq 0.05$) or the same ($p > 0.05$) relative to respective business-as-usual approaches (see experimental procedures for more details). This approach, referred to as "vote counting,"[69] allowed us to assess the general utility of each innovation compared to business-as-usual approaches, but it comes with some limitations. For example, we were not able to assess the magnitude by which a given innovation influenced vegetation recovery outcomes.[70] Thus, our results serve as an initial assessment of these innovations given current knowledge that should be built upon once sufficient experimental data are available on each approach to apply a standard meta-analytical framework. Some of the studies assessed may not have detected differences in outcomes between the innovations and business-as-usual approaches (i.e., "same" outcome in Figures 2, 3, and S3) because they lacked the statistical power to do so,[69] highlighting the importance of building and scaling broad collaborative networks to implement field experiments that evaluate outcomes across many contexts with sufficient replication.[71]

Vegetation recovery outcomes

Our findings show that most of these innovations may have the capacity to improve restoration outcomes, especially with respect to the most evaluated recovery indicators of above-ground biomass/carbon accumulation (N = 58) and plant growth (N = 56; Figure 2A). While studies comparing the focal innovations to business-as-usual techniques have increased 5-fold since 2010 (Figure S2), pointing to the recent rapid expansion of these techniques, we also identified shortcomings in our understanding of how they may function at scale.

Across all the recovery indicators evaluated, the innovations generally showed higher or similar recovery of above- (55% of cases) and below-ground (50%) biomass/carbon accumulation, tree growth (46%), plant species diversity (67%), and forest structure (90%) compared to business-as-usual techniques (described in Table 1; Figures 2A and S3; Table S2). The exception was seedling/seed survival, which only improved in 15% of cases where it was evaluated (Figure 2A). Across all vegetation recovery indicators, innovations frequently had higher mean vegetation recovery values: mixed plantings (71% of cases),

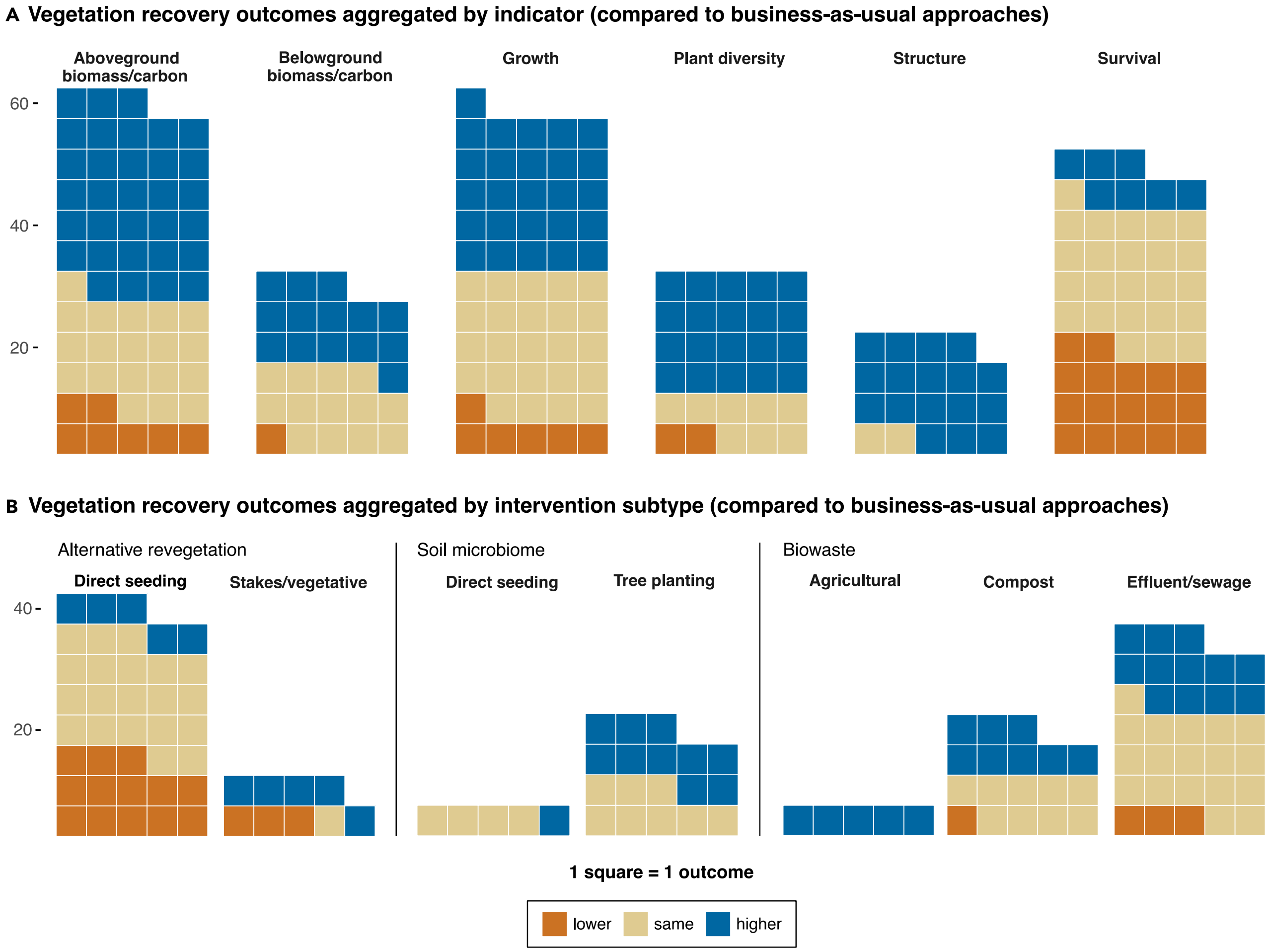

Figure 2. Vegetation recovery outcomes for the seven innovations aggregated by indicator and intervention subtypes
(A) Vegetation recovery outcomes grouped by indicator across all innovations, compared to business-as-usual (i.e., control) approaches.
(B) Vegetation recovery outcomes separated by intervention subtypes (where evaluated), compared to business-as-usual approaches. Outcomes of interventions that were not split into subtypes in the studies evaluated (biochar, economic species, mixed plantings, spatially patterned planting) are shown in Figure 3. Each square represents an outcome relative to its respective control (see Table 1; extracted from 239 observations in 143 studies), with the color indicating either a lower (orange squares; $p \leq 0.05$), the same (beige squares; $p > 0.05$), or a higher (blue squares; $p \leq 0.05$) mean recovery value. See Tables S2 and S3 for a tabular version of results.

economic species (70%), biochar (50%), soil microbiome (48%), biowaste (44%), and spatially patterned planting (39%) compared to business-as-usual (Figure 3). Alternative revegetation approaches had higher recovery values for only 20% of outcomes, where we observed lower recovery values than business-as-usual approaches in over one-third of cases (Figure 3; Table S3), driven by the generally lower recovery values observed for direct seeding (Figure 2B; Table S4).

Whereas these approaches often led to positive outcomes, it is important to consider the context in which they have been evaluated. For example, direct seeding has been widely tested as an alternative to planting tree seedlings (N = 38), whereas planting stakes has not (N = 9). Moreover, soil microbiome recovery has mostly been tested for tree seedlings (N = 18) but not direct seeding (N = 5), while effluent/sewage addition is by far the most tested biowaste product in a restoration context (Figure 2B), illustrating that some of these approaches need to be evaluated further to fully understand the mechanisms underlying improved outcomes. It is also important to acknowledge the potential influence of publication bias on our results, as the high proportion of positive outcomes observed for certain innovations could be driven in part by the tendency to publish restoration successes but not failures. While a growing list of publications have specific article types designed to publish specific restoration outcomes,[72] the community needs more emphasis on gathering and synthesizing drivers of restoration successes and failures.[73] Additionally, the geographical extent over which innovations have been evaluated is limited in certain cases. For example, biowaste and biochar have mainly been evaluated in temperate regions, whereas mixed plantings have mostly been tested in the tropics (Figure 1; Table S5), highlighting that further assessments should prioritize filling these geographical gaps.

Relative costs, cost-benefits, and trade-offs

Whereas the innovations evaluated mainly had positive or similar outcomes compared to business-as-usual approaches

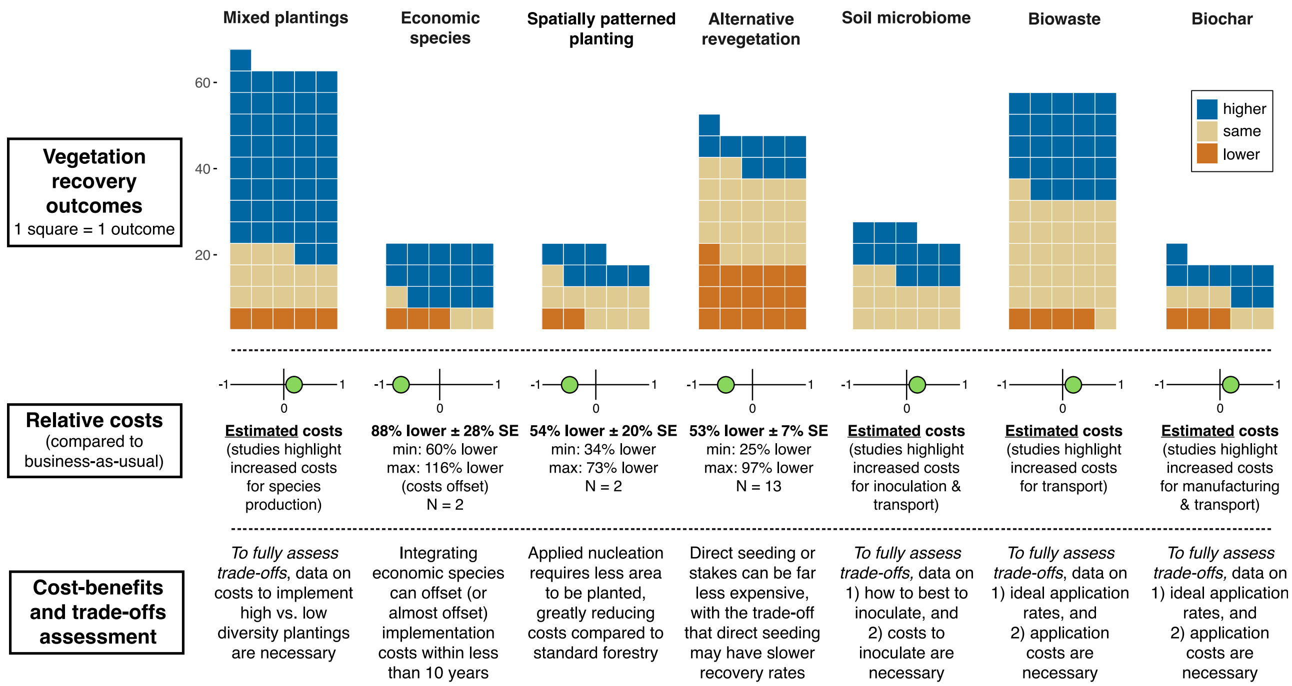

Figure 3. Vegetation recovery outcomes and relative costs of the innovations evaluated compared to business-as-usual approaches (Table 1), and a cost-benefit and trade-off assessment for each innovation
Each square represents an outcome relative to each respective control (see Table 1), with the color indicating either a lower (orange squares; $p \leq 0.05$), the same (beige squares; $p > 0.05$), or a higher (blue squares; $p \leq 0.05$) or mean recovery value. Relative costs were sourced from 17 studies reporting costs found during the systematic review. For all innovations where no cost data were found, by fully reading each study, we estimated that relative costs increased based on costs referenced but not directly quantified (e.g., transportation); the numeric estimate of relative costs for those innovations is provided only for visualization purposes. See Table S4 for a tabular version of the vegetation recovery outcomes.

(Figures 2 and 3), their true utility can only be fully assessed by considering their costs, cost-benefits, and trade-offs in terms of vegetation recovery outcomes. However, we only found cost data for three innovations in the literature, and only two studies each for two of those innovations (economic species and spatially patterned planting). Nevertheless, the innovations generally fell into three categories when comparing implementation costs to business-as-usual approaches (Figure 3).

Two of seven innovations directly reduced restoration costs relative to business-as-usual

Both alternative revegetation and spatially patterned planting cut implementation costs in half on average. Considering that spatially patterned planting rarely had lower vegetation recovery outcomes than business-as-usual (only 11% of cases), this approach is promising for both reducing costs and improving outcomes (Figure 3). By contrast, although alternative revegetation costs less, 35% of studies noted lower mean recovery values compared to controls (Figure 3), primarily because direct seeding has lower survival rates compared to planting seedlings (Figure S3). This emphasizes the importance of considering the ecological trade-offs of this approach, as highly reduced up-front costs for direct seeding come with the trade-off that recovery may be slower. For spatially patterned planting, recovery rates were generally faster or equivalent to business-as-usual in terms of plant diversity and structure indicators. However, above-ground biomass/carbon accumulation and plant growth were faster in business-as-usual plantations in two of four cases for spatially patterned planting (Figure S3), underscoring trade-offs in the ecological outcomes of these approaches—in this instance facilitating biodiversity recovery but not necessarily above-ground carbon accumulation.

One innovation was able to entirely offset implementing costs: Integrating economic species

While we only found two studies that quantified the implementation costs offset by this approach (one in Costa Rica[34] and one in Brazil[35]), both indicated that almost all initial implementation costs could be offset by extracting and selling the wood of the economic species less than 10 years after project implementation. This hybrid approach could also be paired with other cost-effective interventions to not only offset implementation costs but also generate income, providing a financial incentive to communities to implement restoration provided that permits to extract and sell wood can be readily obtained and that a market exists for the species grown (Table 2). In implementing this approach, it is also key to ensure that the permanence of the remaining plantings is prioritized, through improved governance structures or other approaches.[11] This approach comes with the potential trade-off of slower plant biodiversity recovery, similar to traditional forestry techniques that optimize for initial accumulation of above-ground biomass/carbon.[74] Integrating economic species into native reforestation projects may help to mitigate this trade-off, as plant diversity recovery using this approach was slower in only one of the four cases identified (Figure S3).

Table 2. Summary of what each innovation overcomes/adds, its capacity to scale up, and its limitations

Innovation	What it overcomes/adds	Limitations/challenges	Requirements and capacity to scale
Mixed plantings	more taxonomic diversity and function leads to faster recovery[32]	limited by the pool of species that local nurseries produce, often due to limited knowledge about how to produce many native species, which is a large barrier in many regions[75,76]	potentially straightforward to implement if there is a coordinated seed collection and nursery network within a given region, and legal frameworks requiring implementation may be necessary to make high-diversity plantings economically feasible at scale[75–77]
Economic species	provides economic benefit to projects, with the goal of offsetting implementation costs, generating additional income, and gaining landowner support[34,35]	some exotic economic species are invasive or have effects that are difficult to remove (i.e., allelopathy) that may restrict native plant recruitment, and care must be taken not to damage restoration plantings when harvesting[78,79]	possible to implement where there is ongoing production forestry and native forest restoration, as this approach simply combines the two; requires a local market for the economic species planted, a large enough scale of production for income generation from a given economic species to be feasible,[80] and thorough planning with local stakeholders to decide on the abundance of economic vs. native species used in plantings
Spatially patterned planting	overcomes the homogeneous structure of plantations and decreases the area needed to plant relative to the area under restoration[36,81]	non-systemic planting can be perceived as "messy" and/or difficult to implement, requiring a need to communicate how these approaches meet local needs to ensure their adoption. The project area must be large enough for plantings to establish well, and there must be sufficient seed dispersal for subsequent recovery to occur[38,82]	implemented in a manner similar to that of forest plantations, which is straightforward to scale up as the infrastructure already exists; difficult to implement unless a project provides a framework for landholder income generation[38]
Alternative revegetation	helps to overcome seedling production bottlenecks, generally more cost-effective than planting seedlings[41,45]	only works for certain species and ecosystems; requires large quantities of collected seed, which often are unavailable, or suitable trees to cut stakes from; for direct seeding, seed predation and increased mortality rates must be addressed[41,83]	direct seeding has been applied on large scales with high but variable success in grasslands and some forests, where it is still minimally used; requires the availability of large quantities of seeds at low cost, which is rare, and mechanizing application, which is only feasible on relatively flat terrain[44]; stakes are widely used as living fences, but use in a restoration context may be limited to small scales due to difficulty in sourcing material, and is limited to a subset of species with the ability to establish vegetatively[47]

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Table 2. *Continued*

Innovation	What it overcomes/adds	Limitations/challenges	Requirements and capacity to scale
Soil microbiome	stimulates plant biomass recovery and diversifies below-ground communities[54,56]	needs to better understand where to source microbial populations without damaging source populations and also consider that pathogens and weed seeds can be introduced inadvertently[56]	straightforward to implement when there are nearby forest remnants for access to and production of live inocula, but requires the development of new ways to introduce wild-type microbial communities that do not require mass soil excavation from intact donor habitats[54,56]
Biowaste	can speed regeneration with one application; can overcome the economic and environmental impacts of chemical fertilizers[61,64]	expensive to apply to sites that are far from a waste source[84]; may bring legal, health, and social obstacles when applying in a restoration context[60]	requires a local source of abundant waste material to minimize transportation and application costs[85]; in regions where there is a lot of waste available near degraded lands, there is high potential to apply at scale (e.g., coffee and orange peels); effluent/sewage is present everywhere, which could scale up more easily
Biochar	can increase plant growth by decreasing soil acidity, thereby increasing nutrient availability[65,68]	needs a local, sustainable source of high-quality biochar to be cost-effective[86]	requires the presence of a local biochar production facility to minimize transportation and application costs, which is rare in most parts of the world but is changing rapidly[87]

For four innovations (biochar, biowaste, mixed plantings, soil microbiome), none of the 342 studies reviewed reported data on implementation costs

However, all these approaches come with slightly to substantially higher costs (e.g., for material production/transport) that must be better quantified to fully assess their relative costs and trade-offs compared to business-as-usual. For instance, both biowaste and biochar resulted in reduced plant survival in three instances, potentially due to suboptimal application rates.[88] That said, of all the innovations, mixed plantings by far had the greatest proportion of higher recovery values compared to controls (71%; Figure 3), and this held true across most vegetation recovery indicators (Figure S3), highlighting that improving seed harvesting practices and nursery infrastructure should be prioritized so that high diversity plantings can be scaled (Table 2).[75,89]

OVERCOMING BARRIERS TO UPSCALING RESTORATION INNOVATIONS

The task of determining how, why, when, and where to restore forests is complex, but many strategies can facilitate restoration design once clear biophysical and/or socioeconomic goals are defined.[90] By defining clear objectives, efficiency is increased and extraneous costs are minimized. It is important to consider that progress made toward goals is influenced not only by the suitability of the restoration approaches used[91] but also by the state of degradation within a given site and the broader landscape.[92] Thus, while the innovations in the design of assisted restoration projects outlined above hold great potential to help projects meet their goals and recover targeted ecosystem processes (Figures 2 and 3), each has particular benefits, limitations, and requirements for implementation (Table 2). Moreover, these interventions will be successful across landscapes only if they improve local livelihoods and are designed by multi-stakeholder coalitions that integrate local communities, government agencies, and institutions.[93] Within these contexts, there must be a strong focus not only on tailoring restoration interventions to meet socioeconomic needs to ensure their long-term success but also on tracking the costs and outcomes of a wide variety of approaches to better evaluate their potential for widespread implementation. If these obstacles can be overcome, then these and other innovations could greatly accelerate the pace of ecological restoration in terms of vegetation recovery outcomes.

Infrastructure and practice refinements required to upscale restoration innovations

In highlighting the potential benefits of scaling these restoration innovations, our review emphasizes some critical needs with respect to improving both restoration infrastructure and best practices (Table 2). Although careful selection of a diverse suite of species can improve outcomes of mixed plantings[90] (Figure 3), expanding this approach is often constrained by the limited availability of species in nurseries and knowledge about how best to propagate them. Thus, greatly expanding nursery infrastructure and the capacity to source and germinate seeds,[75,76] as well as generally increasing the size of the restoration economy and labor force,[94,95] is critical to scaling this and other approaches. Scaling direct seeding is especially limited by the large quantities of seeds needed to account for losses to predation, failed germination, and mortality of small seedlings.[41] To enable the widespread use of biowastes, major barriers must be overcome, including the development of infrastructure needed to properly manage these wastes,[84] and alignment with local waste management health regulations, which may legally restrict their use in certain contexts.[60] For biochar use to become viable, production capacity must be built worldwide. Whereas there are good examples of sustainable biochar production at small scales using sources such as Brazil nut shells,[96] the use of biochar has not been widely adopted because it has not been economically attractive to farmers or other landholders.[86] Additionally, the accessibility of restoration sites also constrains the application of both biowaste and biochar approaches as they require large amounts of material to be transported to restoration sites.[61,85] To address this, the biochar industry is rapidly reducing costs by producing biochar closer to agricultural areas, but until recently these efforts have primarily been implemented in the Global North.[87]

In addition to improving infrastructure, key research and development must take place to refine best practices that allow these innovations to be implemented at scale. For example, expanding the application of direct seeding requires the development of mechanized approaches that have only been effective at a large scale on relatively flat terrain.[44] While some groups have pioneered the use of drones to broadcast seed over large areas,[97] improving the ability of drones to apply seeds to suitable locations is necessary to ensure effective application of this approach.[98] Moreover, there is widespread potential to take advantage of soil microbiome restoration to facilitate the recovery of entire ecosystems, but it comes with potential risks as this approach can introduce both symbionts and pathogens. Although many pathogens are native to ecosystems and play an important role in the maintenance of above-ground biodiversity,[99] there is the risk of introducing non-native pathogens and invasive microorganisms. Additional research is needed to understand the minimum information necessary to ensure that these approaches are executed responsibly and in a way that minimizes the cost to practitioners and impacts on source ecosystems.[56] There are also context-dependent challenges associated with applying biochar and biowastes within a restoration context. For biochar, the source material and the temperature at which a biochar is produced matter immensely as different biochars can have contrasting effects on soil nutrient cycling, either enhancing or decreasing plant yields, depending on the context.[100] Furthermore, application rates for each type of biowaste must be optimized as excessive application rates can negatively affect aspects such as ecosystem carbon accumulation[101] and seedling survival rates.[88]

A critical need to assess restoration costs and outcomes at scale

Despite the importance of assessing the costs and outcomes of implementing interventions at large scales,[9,29] fewer than 5% of the relevant studies we reviewed assessed implementation costs for the focal restoration innovations (N = 17), and no studies compared the costs of different innovations in the same system. Furthermore, outcomes were rarely evaluated across the large spatial extents and broad contexts necessary to robustly evaluate their efficacy.[102] Strikingly, across the studies assessed (N = 123), 90% were conducted on very small scales (<1 ha) and only 4.4% (N = 6) were evaluated at scales of 100 ha or more. A similar pattern has been noted for studies of natural regeneration[103] and assisted restoration and land management approaches differing from business-as-usual tree planting.[22] Additionally, above-ground biomass/carbon recovery and plant growth and survival outcomes were measured much more often than others, and no studies evaluated vegetation structure recovery for the biochar and soil microbiome innovations (Figure S3). Without rigorously assessing the costs of restoration in parallel with landscape-scale restoration outcomes we can only speculate about the feasibility of scaling specific restoration interventions. This points toward a need to robustly assess restoration costs and outcomes at landscape scales across a wide variety of indicators, ideally across distributed experimental networks,[104] to determine which approaches speed ecological recovery and also (1) demonstrate the necessary economies of scale to make their application viable,[9] and (2) increase their permanence by directly benefiting local communities.[11]

Our review provides a first step toward categorizing the relative costs and cost-benefits of focal restoration innovations. We were able to group three out of seven as generally reducing (alternative revegetation, spatially patterned planting) or offsetting implementation costs (economic species), with important trade-offs in vegetation recovery outcomes to consider (see the section "Relative costs, cost-benefits, and trade-offs"; Figure 3). However, no studies reported on the costs to implement the other four innovations (see the section "relative costs, cost-benefits, and trade-offs"). This dearth of standardized data on costs is systemic across the restoration literature.[29] In response, The Economics of Ecosystem Restoration initiative[28] has started to address this issue by creating a framework to quantify the costs and benefits of individual or mixes of restoration interventions, while widely distributed surveys of restoration actors have also addressed this gap by categorizing costs and practices associated with specific components of restoration implementation. For example, Brancalion et al.[26] identified that over half of assisted restoration costs in Brazil are generally associated with inputs that could be used more cost-effectively (e.g., fencing, seedlings, herbicide), and that maintenance of assisted restoration takes place on short time scales due to a lack of long-term funding. Despite these recent advances, there is a critical need to better assess the economics of restoration to develop economies of scale for restoration implementation that ensure its feasibility and success,[9] and to understand the dynamics of public and private finance flows to restoration to ensure that each aspect of the process is adequately funded.[105,106]

Another important limitation is that restoration interventions were evaluated individually in all the studies we reviewed. Combining and testing approaches (e.g., merging high diversity species mixes with innovations that reduce or offset implementation costs) could create synergies that bolster the design of effective restoration interventions, enabling their application in an even more economically scalable manner. For example, given the goal of restoring a native forest ecosystem, combining all seven innovations (or a subset) to evaluate the outcomes of establishing high diversity mixes of native tree species with a mixture of seedlings, direct seeding, and stakes, using a spatially patterned planting approach that integrates soil amendments (soil microbiome, biochar and/or biowaste) suitable for the local context (i.e., surrounding landscape structure, level of soil degradation, and existing local infrastructure and legal frameworks) could yield dividends. As part of this, initial implementation costs could be offset with strategic plantings of economic species. By optimizing mixtures of these innovations and others using systematic assessments of their cost-benefits, trade-offs, and synergies, we can begin to break down barriers to implementing restoration at large scale.

Finally, the vote counting approach we used to assess the effectiveness of each innovation compared to business-as-usual approaches has limitations. Underpowered studies could have failed to detect benefits of the innovations in certain cases, and we could only assess the direction, not the magnitude, of the effects of the innovations.[69] That said, our initial evaluation of these innovations highlighted their potential utility (i.e., evidence of an effect of their application) as they generally showed higher or similar recovery values to business-as-usual approaches (Figure 2).

Ensuring that interventions that differ from business-as-usual approaches meet socioeconomic needs

Thus far, we have focused on how restoration innovations can be tailored to local biophysical conditions to improve outcomes, but meeting socioeconomic needs and desires with specific approaches is equally as important. A multitude of initiatives and studies highlight the need to involve local stakeholders in the entire restoration process, ensuring that (1) stakeholder livelihoods are met; (2) local, traditional, and Indigenous knowledge, rights, and values are integrated into project plans; and (3) restoration projects rely on local labor markets, which is of the utmost importance to restoration success.[27,94,107] However, there is often a mismatch between the ecological goals of restoration and the socioeconomic needs of communities.[108] For example, spatially patterned planting methods may not be attractive to landholders who prefer the widespread planting of economically valuable species to maximize land usage, and[38,109] these non-systemic planting approaches can be perceived as disorganized.[38,82,109] Furthermore, the use of biowastes in restoration have faced challenges because of a lack of a clearly defined legal framework for their use and broad differences across countries.[59,60] Thus, while the adoption and success of novel restoration interventions is contingent on ensuring that socioeconomic needs are met, whether specific restoration interventions will be applied within a given context may be highly variable.

Despite challenges surrounding their implementation, key capacity-building initiatives have increased the use of potential restoration interventions. For biochar, a study in Poland showed that farmer adoption of biochar use increased dramatically simply by providing public conferences on the potential benefits of using this amendment.[110] There are also excellent examples of community-engaged projects and training programs helping to shift farmers' perspectives toward implementing small-scale reforestation in the tropics. One example is BioPaSOS (www.biopasos.com), a multi-institution initiative across Central and South America encouraging the expansion of silvopastoral systems (i.e., hybrid grazing/agroforestry systems). By providing resources and workshops to cattle ranchers, this initiative has demonstrated how silvopastoral systems can directly meet farmers' needs, and it trained over 1,000 ranchers using a standardized outreach and project co-creation methodology that results in not only increased tree cover on farms but also additional income for farmers by planting economically valuable trees.[111]

CONCLUSION

Realizing the tremendous potential of forest restoration to help address the global threats of biodiversity loss, food insecurity, pandemics, and climate change[112–116] requires a balanced portfolio of ecosystem regeneration approaches. The promise of each approach comes with specific benefits and trade-offs, and all must be tailored to local ecological and social conditions to ensure their success. Our review highlights how various innovations may catalyze global restoration initiatives by increasing vegetation recovery rates. The innovations assessed had a marked capacity to catalyze vegetation recovery across a variety of contexts, with improved outcomes in over two-thirds of cases compared to business-as-usual approaches (particularly for mixed-species plantations and integrating economic species). Additionally, certain innovations may help restoration efforts scale up by reducing or offsetting implementation costs. However, uncertainty remains about the economic feasibility and large-scale ecological impacts of scaling restoration approaches, as less than 5% of the studies identified documented costs and 90% assessed outcomes at scales of less than 1 ha. This further highlights the need for a globally coordinated effort to assess the socioeconomic and ecological feasibility of scaling each and every potential restoration intervention. It is time to implement and assess the efficacy of these and other interventions at scale, while working to ensure that interventions are socially beneficial and meet stakeholder needs; we already have the tools and the groundswell of support for global restoration needed to make this happen.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests should be directed to and will be fulfilled by the lead contact, Leland K. Werden (lwerden@gmail.com).

Materials availability

This study did not generate new unique materials.

Data and code availability

A complete list of the studies and corresponding data used for analysis were deposited in Mendeley at https://doi.org/10.17632/9x4hntz358.1.

Systematic review of the published literature

We systematically reviewed the literature published on each of the innovations using a Web of Science keyword search (February 24, 2023). We focused on summarizing the impact (i.e., outcome) of each innovation on assisted forest recovery in terms of woody vegetation, above- and below-ground biomass/carbon, tree growth/survival, plant diversity, and forest structure. A flowchart detailing the full literature review and screening process is presented in Figure S1.

For each Web of Science query, our search terms began with the keywords for the innovation:

(1) Alternative revegetation (N = 700 studies): *TOPIC: ((direct seeding* OR *direct-seeding* OR *vegetative propagation* OR *stake*)* …
(2) Biochar (N = 591 studies): *TOPIC: ((biochar** OR *charcoal** OR *ash*)* …

(3) Biowaste (N = 365 studies): *TOPIC: ((agricultural by products** OR *agricultural waste** OR *agriculture by products** OR *agriculture waste** OR *compost*)* …
(4) Economic species (N = 143 studies): *TOPIC:((exotic native mix** OR *economic native mix*)* …
(5) Mixed plantings (N = 3,953 studies): *TOPIC: ((mixed species plantation** OR *high diversity plantation** OR *diverse plantation** OR *species richness*)* …
(6) Soil microbiome (N = 455 studies): *TOPIC: ((soil transplant** OR *soil inocul** OR *soil microbiome*)* …
(7) Spatially patterned planting (i.e., Applied nucleation) (N = 249 studies): *TOPIC: ((applied nucleation** OR *spatially patterned planting** OR *tree islands*)* …

The innovation keywords were followed by keywords on assisted forest recovery and the indicators of interest: … AND (*biomass** OR *carbon** OR *agb* OR *recover** OR *accumulat** OR *structure** OR *plant composition** OR *plant biodiversity** OR *plant richness** OR *growth** OR *survival**) AND (*forest**) AND (*restor** OR *rehabilitat** OR *revegetat** OR *reforest** OR *afforest**)). For example, the full search terms for alternative revegetation were as follows: *TOPIC*: ((*direct seeding* OR *direct-seeding* OR *vegetative propagation* OR *stake**) AND (*biomass** OR *carbon** OR *agb* OR *recover** OR *accumulat** OR *structure** OR *plant composition** OR *plant biodiversity** OR *plant richness** OR *growth** OR *survival**) AND (*forest**) AND (*restor** OR *rehabilitat** OR *revegetat** OR *reforest** OR *afforest**)). We included the term *afforest** because "afforestation" is used inconsistently in the literature and sometimes refers to reestablishing forests where they used to be present naturally. That said, we removed all studies that used assisted restoration to establish trees in ecosystems without natural tree cover (e.g., grasslands), as these approaches can lead to deleterious effects on biodiversity and ecosystem processes.[117]

Our initial searches yielded 6,456 studies in total. We used ASReview[118] to facilitate screening titles and abstracts, selecting all studies (*N* = 342) that met our inclusion criteria: studies (1) that were implemented in the field (i.e., not in a greenhouse or lab) and in natural ecosystems (e.g., not urban), with a target of restoring toward natural ecosystems; (2) in biomes dominated by woody vegetation (i.e., forests, woodlands, shrublands, mangroves); (3) that included empirical data on recovery of woody vegetation above- and below-ground biomass/carbon, tree growth/survival, plant diversity, or forest structure OR data on costs of implementation (hereafter referred to as "indicators"). We fully reviewed all these studies and selected those that directly compared an innovation with a business-as-usual control at the same site with equivalent baseline conditions (e.g., a monoculture plantation control for the mixed-species innovation at the same site; see Table 1), or that included data on the costs of implementing an innovation and/or a business-as-usual approach. This narrowed to a final pool of 143 studies from which to extract vegetation recovery outcomes data (one of which evaluated two innovations), and 17 studies from which to extract implementation costs data. All 143 studies included sufficient replication to estimate the variance of an indicator within treatments of interest (i.e., innovations and business-as-usual controls) and compare treatment means with pairwise statistical tests. When possible, we focused on primary studies, but we included 10 meta-analyses in the final study pool because they detailed important broad-scale outcomes for certain innovations (*N* = 11 total outcomes). Including these meta-analyses in our study pool did not notably shift the outcomes observed for individual innovations, so we included them in our final dataset.

From the final pool of studies (*N* = 143) we extracted the following information:

(1) Innovation: "Alternative revegetation" OR "Biochar" OR "Biowaste" OR "Economic species" OR "Mixed plantings" OR "Soil microbiome" OR "Spatially patterned planting".
(2) Subtype of intervention if there was a logical split within an innovation:
 (a) Alternative revegetation: "direct seeding" OR "stakes/vegetative propagation"
 (b) Biowaste: "agricultural" OR "compost" OR "effluent/sewage"
 (c) Soil microbiome: "direct seeding" OR "tree planting"
(3) Location (if available): In latitude/longitude, coded using precise location or location names provided in a study.
(4) Biome: Where the innovation was tested using the RESOLVE terrestrial biome classification.[119]
(5) Indicator measured for woody vegetation recovery (standardized by area): "aboveground biomass/carbon" OR "belowground biomass/carbon" OR "growth" (i.e., tree growth) OR "plant diversity" (i.e., woody plant diversity) OR "structure" (i.e., vegetation structure in terms of woody vegetation cover, stem density, basal area) OR "survival" (i.e., tree seed, seedling, or stake survival).
(6) Vegetation recovery outcomes: To characterize how each innovation compared to business-as-usual approaches in terms of key recovery indicators at the conclusion of each study, we coded vegetation recovery outcomes as lower, higher ($p \leq 0.05$), or the same ($p > 0.05$) relative to each respective control (see Table 1) based on the results of pairwise statistical comparisons within each study for indicator × innovation combination (referred to as a vote counting approach).[69] For example, above-ground biomass/carbon (the indicator) in a mixed planting (the innovation) could be either lower, higher, or the same (the outcome) as a monoculture planting at the conclusion of a study.
(7) Costs (per hectare) of implementation for the innovation and/or business-as-usual control approach.
(8) The spatial scale at which an innovation was evaluated in hectares.

Summaries of outcomes

In total, we extracted data on 239 total vegetation recovery outcomes across all the innovations and data on implementation costs from 17 studies. We summarized the vegetation recovery outcomes by innovation, indicator, and intervention subtype (if applicable) with waffle charts (Figures 2, 3, and S3; *waffle* package). When possible, we calculated the mean relative cost (± SE) for the implementation and maintenance of an innovation (Figure 3) compared to its business-as-usual control (Table 1). All data analyses were performed using R version 4.2.1.[120]

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.07.011.

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AUTHOR CONTRIBUTIONS

L.K.W., R.J.C., and T.W.C. conceptualized the project, with input from all authors. L.K.W. and K.S. conducted the literature review and extracted data. L.K.W. conducted the data analysis. L.K.W. wrote the first draft of the manuscript, and all authors contributed to revisions.

DECLARATION OF INTERESTS

T.W.C. is the founder of Restor Eco AG and serves on the Foundation board in a pro bono capacity. T.W.C., C.A., K.D.H., and R.J.C. are members of Restor's Science Advisory Council. C.A. is the founder of Funga, to which T.W.C. is a scientific advisor.

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