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The intervention continuum in restoration ecology: rethinking the active-passive dichotomy

Running head: Rethinking the active-passive dichotomy

Robin L. Chazdon[1], Donald A. Falk[2], Lindsay F. Banin[3], Markus Wagner[4], Sarah Wilson[5], Robert C. Grabowski[6], Katherine N. Suding[7]

[1]Tropical Forests and People Research Centre, University of the Sunshine Coast, Sippy Downs QLD 4556, Australia

[2]School of Natural Resources and the Environment, University of Arizona Tucson, AZ 85721 USA

[3]UK Centre for Ecology & Hydrology, Bush Estate, Penicuik, Midlothian, EH26 0QB, UK

[4]UK Centre for Ecology & Hydrology, Crowmarsh Gifford, Wallingford, Oxon OX10 8BB, UK

[5]School of Environment, University of Victoria, Canada

[6]School of Water, Energy and Environment, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK

[7]Ecology and Evolutionary Biology and Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, CO 80309-0450, USA

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Abstract

The distinction often made between active and passive restoration approaches is a false dichotomy that persists in much research, policy and financial structures today. We explore the contradictions imposed by this terminology, and the merits of replacing this dichotomy with a continuum-based intervention framework. In practice, the main distinction between “passive” and “active” restoration lies primarily in the timing and extent of human interventions. We apply the intervention continuum framework to forest, grassland, stream, and peatland ecosystems, emphasizing that a range of restoration approaches within the scope of ecological or ecosystem restoration are typically employed in most projects, and all can contribute to the recovery of native ecosystems and prevention of further degradation. As restoration is fundamentally about the recovery of ecosystems, eliminating human sources of degradation is essential to enable ecosystem recovery processes, regardless of subsequent interventions that may be needed to assist recovery. Our review of restoration practices involving different levels of intervention highlights the benefits of recognizing a broader suite of restoration interventions in the financial and policy frameworks that currently underpin restoration activity. Effective restoration interventions emerge from an understanding of nature’s intrinsic recovery potential and overcoming specific obstacles that limit this potential.

Key words: active restoration, ecosystem degradation, ecosystem recovery, passive restoration, restoration strategy, succession

Conceptual Implications

- In practice, the main distinction between “passive” and “active” restoration is in the timing and extent of human interventions
- Interventions to repair ecosystems are often valued more than halting degradative processes or removing obstacles to natural recovery
- A continuum-based intervention framework is more useful, practical, and representative of actual restoration practice
- We apply the intervention continuum framework to restoration of forests, grasslands, rivers, and peatlands

Introduction

The practice and definition of ecological restoration focus on deliberate and active interventions (SER 2004; Clewell & Aronson 2013). The unaided process of natural regeneration or ecological succession does not necessarily fall within the definition of restoration, as it can proceed without human agency. This logic casts the term “passive restoration” out of the ecological restoration lexicon, or at least places it on its periphery. The focus on restoration as human activity has spawned engineering and accounting approaches to restoring ecosystems. Restoration practice has become institutionalized as a time-bound project with explicit goals, approaches, and deliverables.

The premise that restoration is an explicitly human activity stems from a worldview that humans are separate from and have dominion over nature. People are the agents of restoration, and ecosystems are the targets. People are responsible for fixing the damage they caused, and engagement in restoration “interventions” is a social and political act of defiance against the continued degradation and transformation of ecosystems. The emphasis on actions to restore ecosystems can overshadow the important work of halting degradative processes and assessing the capacity of ecosystems to recover after conversion or degradation.

An alternative view holds that restoration is fundamentally about ecosystem recovery, a natural process that is an intrinsic property of ecosystems as they adapt to changing conditions (Chazdon 2014; Falk 2006). Biological systems at all levels of organization have evolved myriad mechanisms to recover from perturbations. Ecosystems do the work of restoration; people may guide or assist this process. The ability of ecosystems to recover following damage or destruction is a matter of human concern, but not of human agency. People can participate in this recovery process by halting degradation and enabling natural mechanisms of recovery, but are not the source of recovery capacity. This view emphasizes the need to (1) identify processes and drivers of ecosystem degradation; (2) consider the inherent capacity for natural recovery inputs for decisions regarding potential restoration interventions (Prach et al. 2020); and (3) thoroughly assess options for ecosystem recovery during initial planning stages.

These contrasting views underlie the persistent and false dichotomy between “passive” and “active” restoration. What is often dismissed as “passive restoration” actually draws directly on the processes by which natural systems recover when human-caused degradation is eliminated or significantly reduced. Unfortunately, despite how essential these processes are, they are not recognized or rewarded in the same way as active restoration interventions, presenting a significant hurdle for restoration practitioners (McDonald 2021). Ironically, the act of “fixing” a broken ecosystem is valued more than the work of halting degradative processes or removing obstacles to natural recovery. These misguided values can lead to inefficient distribution of limited resources and short-sighted restoration outcomes.

Here, we examine how these terms are used today in the practice of ecological restoration. We expose the contradictions imposed by the terminology of “passive” vs. “active” restoration, and emphasize the merits of replacing this dichotomy with a continuum-based intervention framework that is more useful, practical, and representative of actual restoration practice (Prach et al. 2020). We apply the continuum framework to restoration of forests, grasslands, rivers, and peatlands as examples. These applications emphasize the central importance of ecosystem recovery processes in the conceptualization and practice of ecological restoration.

The passive-active dichotomy hinders ecological restoration

The categorical distinction between active and passive restoration persists in much research and policy today, with detrimental effects on both practice and research. In many contexts, restoration has become synonymous with the interventions used (Chazdon et al. 2020). For example, most private-sector financing and government financing is oriented toward active restoration interventions. In forest restoration, tree planting may be undertaken without duly considering the natural regenerative capacity of the land and local biota and, in some cases, replacing early (and often messy) successional vegetation with neat rows of planted seedlings (Holl & Brancalion 2020). The focus on recovery of complex, natural ecosystems (that often include people) is easily overlooked. Land ownership and management rights also influence preferences for restoration interventions. The view of restoration as a “land use,” rather than as an approach to assist the recovery of an ecosystem and its biotic community, further marginalizes the role of natural recovery processes and associated indigenous management practices in favor of more highly managed or commercially-focused interventions. Restoration is often seen as an action taken to modify or “improve” land use.

In practice, the main distinction between “passive” and “active” restoration is in the timing, objectives, and extent of human interventions. The actions required to eliminate human sources of degradation are essential for enabling ecosystem recovery processes, regardless of the kind of restoration interventions applied. In the case of natural recovery, the removal of human disturbances is the only intervention applied (Holl & Aide 2011). The “passive” phase therefore refers only to the post-disturbance recovery process. For example, fencing out livestock, fallowing cropland, removing over-abundant lianas or thinning and controlled burns in fire-suppressed forests can be effective actions to remove effects of human disturbance in an effort to re-establish natural disturbance regimes. In some circumstances, controlled livestock grazing can suppress invasive grasses and promote seed dispersal (Miceli-Mendez et al. 2008), stimulating recovery of wooded ecosystems.

Ecosystem recovery proceeds most quickly in areas with a history of less severe or intensive degradation, in close proximity to propagule sources without dispersal barriers (Holl & Aide 2011), and in sites with moderate productivity and low levels of abiotic stress (Prach et al. 2020). The literature on passive recovery tends to compare outcomes of active interventions with natural regeneration, rather than emphasize how the two approaches can be complementary (e.g., Crouzeilles et al. 2017; Reid et al. 2018; Holl & Brancalion 2020). The persistent dichotomy also fails to recognize and account for the increasing and widespread adoption of assisted natural regeneration as part of the spectrum of restoration interventions practiced in different contexts (Shono et al. 2020, Standards Reference Group 2021).

Ecosystem recovery takes time, even under optimal conditions. As a consequence, relying on unassisted recovery is often viewed as too slow and uncertain to accommodate the timetables and performance expectations of practitioners, managers, or funding agencies (Zahawi et al. 2014). Active restoration approaches are often motivated by the desire or mandate to transform a degraded ecosystem to a restored ecosystem quickly. Such efforts can be less effective for achieving ecosystem recovery than allowing a more gradual progression of states. Intensive restoration interventions can lead to extensive mortality of naturally regenerating seedlings planted in the wrong place or time. By-passing early successional stages to “accelerate” ecosystem recovery can also negatively affect populations of early successional specialists. In Europe, river restoration measures are implemented and monitored within 6-year cycles (European Community 2000). This time period may not be sufficient to assess the ecological response to restoration interventions, especially if other factors (e.g. water quality) are affecting the ecological community (Palmer et al. 2010).

Rejecting this dichotomy, we posit that ecological restoration practices can be unified along an intervention continuum (Figure 1, Table 1). The intervention continuum concept recognizes that restoration interventions should be case-specific and tailored to specific processes that drive the degradation and recovery of focal ecosystems. We present a decision tree involving four steps to assist decision-making by implementers and practitioners following the intervention continuum framework (Box 1). We recognize that many experienced practitioners are already employing actions along a continuum; the concept is relevant to (1) emerging organizations newly engaging in restoration; (2) scientists assessing and synthesizing the efficacy of restoration approaches; (3) funders who are seeking to provide resources to support restoration activities; and (4) policy-makers and decision-makers who are delivering restoration strategy.

Figure 1 here

Box 1 here

Ecosystem-specific frameworks based on the intervention continuum

Forest ecosystems

Restoration of forest ecosystems follows a wide range of approaches (Figure 1, Table 1) that draw from well-established practices in forest management, grounded in an understanding of forests as dynamic ecosystems (Binkley 2020). On publicly-owned lands, land management philosophy often emphasizes the retention of natural ecosystem dynamics to the greatest possible extent (Christensen et al. 1996; Keeley 2009). Forest restoration practices are also driven by the practicalities of managing landscapes of hundreds to millions of hectares, scales at which micromanagement of ecosystem processes is neither feasible nor desirable (Doyle & Drew 2012; Latawiec et al. 2015).

Table 1 here

Natural recovery of forest ecosystems following large-scale disturbances is influenced by local site conditions and prior land uses, as well as landscape-scale factors that influence colonization and establishment of native species (César et al. 2021). Recovery can generally occur where soils have not been heavily disturbed, and patches of native forest vegetation are adjacent or nearby (Crouzeilles et al. 2020). In former agricultural fields, recovery typically begins with colonization of ruderal herbs, graminoids, and shrubs, followed by light-demanding tree species whose shade promotes the establishment of shade-tolerant mid- and late-successional species (Swanson et al. 2011). These early stages of forest succession provide important habitats for native species of invertebrates and vertebrates that thrive in more open conditions. Establishment of late-successional tree species can take decades or centuries. Some active forest restoration interventions focus on planting seedlings of late successional tree species, bypassing the early successional phases. This approach overlooks the gradual development of ecological legacies such as soil biogeochemical processes and complex trophic pathways over time (Johnstone et al. 2016).

In forest restoration, the term “assisted natural regeneration” (ANR) is often applied to cases where light interventions—including site protection, maintenance, and in some cases strategic tree planting to encourage recovery—are employed to reduce or eliminate sources of degradation that impede forest regeneration or to hasten establishment of diverse native vegetation (Shono et al. 2020). The Society for Ecological Restoration in Australia recently adopted the terms “facilitated regeneration” and “combined regeneration and reintroduction” to describe ANR approaches (Standards Reference Group 2021). In our framework, these interventions are examples of “lightly assisted recovery” and “moderately assisted recovery,” respectively (Figure 1). Light and moderate interventions can also be used to enhance the regeneration of trees used for production of fodder, firewood/charcoal, fruit or timber products (Shono et al. 2020) while also promoting regeneration of native tree species, enhancing biodiversity, and supplying a wide range of ecosystem services such as soil fertility and water quality. Reducing effects of weedy invasive species, creating fire breaks, and fencing are common ways to assist natural regeneration of forests (Figure 1, Table 1).

Moderately-assisted recovery interventions are applied widely in the restoration of post-agricultural lands, or to restore forests affected by logging or by fire suppression. Direct seeding and planting seedlings are the most widely used approaches for restoring forests on post-agricultural lands. Many conifer forests in western North America have become overstocked due to fire suppression and are vulnerable to insect infestation, drought-induced mortality, and catastrophic fires (Abatzoglou et al. 2016; Kautz et al. 2017; Keeley et al. 2019). In these cases, restoration interventions often focus on stand thinning and controlled burns to reduce the potential for extreme fire behavior, and offset drought stress (Addington et al. 2018). When land uses have completely removed soil or altered hydrology or landforms (as with strip-mining or other forms of mining), forest restoration requires intensive and costly initiatives that may include a progression of interventions (Figure 1). Post-mining forest restoration is a costly staged process involving reapplication of retained topsoil, followed by weeding and planting native or exotic "nurse" trees, followed by seeding or planting seedlings of native tree species (Festin et al. 2019).

Restoration following large wildfires characteristically employs the full continuum of interventions. Intensive interventions are employed to treat areas that have burned with high severity effects on vegetation and soils, because these areas are the least likely to recover without assistance, whereas other areas are generally allowed to recover naturally (Walker & del Moral 2009). For example, in the US, immediate post-fire actions are typically conducted under the Burned Area Emergency Response (BAER), which emphasizes intensively assisted recovery (*sensu* Figure 2) with a focus on stabilizing soils to reduce hillslope soil erosion and sediment flux into stream channels (Robichaud et al. 2000, 2009). Once hillslopes are stabilized, the emphasis shifts to re-establishing vegetation. Areas near (<200 m) remnant intact forest are typically allowed to revegetate by natural seed dispersal processes, as conifer seedlings tend to establish close to parent trees (Figure 2; Stevens-Rumann and Morgan 2019). Further into a severely burned patch, beyond natural dispersal distance, land managers may apply lightly or moderately assisted recovery by dispersing seeds by hand or other means (aircraft, UAVs), or planting established (nursery grown or wilding) seedlings. Other areas that shift into early successional vegetation (e.g. dominance by aspen, *Populus tremuloides*) will be left to progress along a post-fire successional sequence (Figure 2).

Figure 2 here

Grassland ecosystems

Temporal continuity of most grassland depends on repeated disturbances that suppress tree establishment. In natural grasslands, disturbance usually consists of fire and/or grazing by native megafauna (Dewar et al. 2021). In semi-natural grassland, it consists of cutting and/or livestock grazing (Prach et al. 2017). In addition, a modulating influence on grassland composition can be exerted by flooding disturbances (Toogood & Joyce 2009). Loss of regular disturbance and subsequent woody plant encroachment is considered a source of degradation for grassland ecosystems worldwide (Ratajczak et al. 2011). Grassland restoration usually requires reintroduction of a suitable disturbance regime, but if woody plant encroachment has occurred, woody vegetation must first be removed (Alford et al. 2012). If conditions exist for reestablishment of target species from the soil seed bank or via dispersal from nearby source grassland, one-off scrub removal, followed by reinstated regular disturbance may be sufficient (Waldén & Lindborg 2018). For natural grassland, this might mean managed disturbances such as controlled burning or livestock grazing (Brudvig et al. 2007; Price et al. 2020).

Where natural recovery of grassland vegetation is not possible, this is usually due to dispersal or establishment limitation (Öster et al. 2009; Grman et al. 2015). Establishment of target species can be limited by lack of suitable mycorrhiza (Koziol & Bever 2017), competition by generalist species that can better exploit high soil fertility (Öster et al. 2009; Wagner et al. 2016), and exotic species invasion (Buisson et al. 2019; Kaul & Wilsey 2021). When these limitations are weak, unassisted restoration can produce reasonable results within 10-20 years, as confirmed for some semi-natural European grassland (Ruprecht 2006; Královec et al. 2009), although full restoration can take substantially longer (Redhead et al. 2014). Moreover, unassisted restoration frequently fails to restore natural grassland if many target species establish poorly from seed (Buisson et al. 2019), or if exotic invasive species keep the system in an alternative stable state (Damasceno et al. 2018; Kaul & Wilsey 2021). To overcome these limitations, restoration interventions for grasslands are available that can be graded based on intensity (Table 1; Figure 3). The best choice depends on the nature and strength of constraints, availability of financial, labor and target species propagule resources, stakeholder requirements, and the time considered acceptable for recovery.

Low-intensity measures to overcome dispersal limitation include seed bank activation via ground disturbance, and grazing management facilitating plant colonization from nearby reference grassland. Another low-cost option is the sowing of low-diversity grass mixtures (Manchester et al. 1999), which is sufficient for restoring agricultural productivity. However, this practice can be counterproductive for full ecological restoration of species-rich grassland, as priority effects from sown grasses may prevent further target species colonization (Fagan et al. 2008). Other approaches, such as transfer of ‘green hay’ or of brush-harvested seed, are used to introduce many target species at once (Kiehl et al. 2010). Sowing high-diversity native seed mixtures can help suppress exotic weed colonization, e.g. in prairie restoration (Kaul and Wilsey 2021), but can be expensive, particularly when applied at larger scales (Walker et al. 2004).

Figure 3 here

Most restored grasslands rely on natural colonization to complement active species introduction, as these methods do not usually establish entire reference communities at once. Although green hay transfer often produces good results, species transfer rates rarely approach 100% (Kiehl et al. 2010). With respect to seed mixtures, even in regions with a well-developed native seed industry, significant gaps remain regarding species availability (Ladouceur et al.

2018; White et al. 2018). Moreover, specialist species often fail to establish when sown during early restoration (Pywell et al. 2003), but may colonize later (e.g. Wagner et al. 2019).

Plug planting, an example of moderate intervention, is usually limited to introducing only a few species (Table 1, Walker et al. 2004). The most intensive interventions to establish target vegetation are turf and topsoil transfer (Manchester et al. 1999). These interventions work well, at least initially (Mudrák et al. 2017; Pilon et al. 2019), but require high-quality donor sites to be destructively 'harvested' (Manchester et al. 1999).

When restoring species-rich grassland from cropland or agriculturally improved grassland, both target species introduction and addressing establishment limitation resulting from excess soil fertility may often be required. In some instances, a gradual decline of soil fertility through regular management may be sufficient, but can take many years (Oomes 1990). One relatively low-effort approach to alleviate moderate excess soil fertility during restoration is to introduce hemiparasitic annual plants. For example, *Rhinanthus* species used in some restored semi-natural European grassland reduce grass dominance and site productivity, and boost target forb establishment (Westbury et al. 2006; Těšitel et al. 2017). Soil nitrogen can be immobilized by incorporating carbon-containing organic materials (Eschen et al. 2006), but this usually requires repeated application (Halassy et al. 2020). Longer-term fertility reduction is achieved by soil inversion by deep ploughing (Glen et al. 2017), or by topsoil removal (Manchester et al. 1999). When dominance of invasive exotic species prevents target species establishment, weed control is key, usually requiring fairly intensive interventions via chemical control or targeted disturbance such as mowing, grazing, or controlled burning (Weidlich et al. 2020; Damasceno & Fidelis 2020). In some instances, restoration of a previous hydrological regime and potentially flooding regime may be required during grassland restoration. Suitable measures can vary in intensity, ranging from limited local measures to much more costly measures to restore large hydrological systems (Jansen et al. 2000).

River and stream ecosystems

Naturally functioning rivers and floodplains are dynamic systems that create spatial mosaics of temporally varying habitats, supporting diverse ecological communities (Ward et al. 2002). Rivers have a great potential for recovery; the level of intervention required depends on the degree to which form, communities and processes have been altered (Palmer & Ruhi 2019; Wohl et al. 2015a).

Unassisted recovery of ecological structure and function (i.e. ecosystem restoration) is possible in most rivers (Wohl et al. 2005). Flowing water drives sediment erosion and deposition within the channel and floodplain, producing variations in topography, soil and sediment characteristics, and hydrology, which are the foundation of physical habitat complexity in river systems (Palmer et al. 2010; Wohl et al. 2015a). The speed of change or recovery are governed by multiple physical factors of the river and catchment, including channel gradient, discharge, sediment loads, sediment grain size, and channel modifications. Upland rivers respond more quickly than lowland ones, because the steeper channel gradients, higher loads of coarse sediment, and high discharges mean that the river has a greater power to reshape the channel, erode banks and alter floodplain topography (Jaehnig et al. 2010). The slower geomorphic process rates in lowland rivers are often used as a justification for assisted recovery; however natural ecosystem engineers (beavers, Brazier et al. 2021; aquatic vegetation and riparian trees, Gurnell 2014) can speed up recovery (Figure 4). Natural recovery can restore function and services, but recovery of the native ecological community depends upon the local and regional species pool, presence of invasive species, and pressures operating at wider scales (e.g. water quality) (Palmer et al. 2010; Wohl et al. 2015a).

Figure 4 here

Lightly assisted recovery considers factors and interventions implemented outside of the channel or upstream of the restoration site to influence river processes or ecology (Table 2). The flow regime is central to river ecosystems (Palmer and Ruhi 2019). Land cover and land use greatly influence the water flow and sediment regimes of a river and, in turn, its form (Vietz et al. 2016; Grabowski and Gurnell 2016; Palmer and Ruhi 2019). A range of sustainable drainage, natural flood management and soil conservation measures can be implemented to naturalize peak and baseflow discharges, reduce diffuse pollution and facilitate geomorphic and ecological recovery (e.g. Grabowski et al. 2019). Upstream dam and reservoir operations can be modified to naturalize the water flow and sediment regimes (Palmer and Ruhi 2019; Wohl et al. 2015b). Aquatic and riparian vegetation can be allowed to develop through fencing or selective thinning and weeding (Table 1; Figure 4). Vegetation and large wood provide important micro- and mesohabitats (Hasselquist et al. 2015; Muller et al. 2016), which can trigger more widespread changes in channel form and habitat complexity through geomorphic processes (Gurnell & Grabowski 2016; Gurnell 2014).

Moderately and heavily assisted recovery are required in situations where historical alterations prevent or limit natural geomorphic and ecological processes from functioning. Moderately assisted recovery includes interventions to remove hard engineering (e.g. revetment), add soft engineering (i.e. wood) to initiate geomorphic processes, or targeted planting of vegetation (Table 1, Figure 4). Heavily assisted recovery is the direct alteration of the form of channel, riparian zone and floodplain, and includes the interventions that are often associated with the practice of river restoration (e.g. channel re-meandering and re-profiling; Table 1). While these measures can be used in any river, they are truly essential only in situations where key elements driving geomorphic change are missing and unable to be restored, or where irreparable change has occurred that limits ecological recovery. A good example is a high-energy river that has incised down to bedrock. If the factors that caused the bed degradation cannot be rectified (e.g. naturalization flow and reconnection of sediment supply), there is limited potential for unassisted recovery.

Peatland ecosystems

Peatlands occur in perpetually wet, anoxic conditions that reduce rates of decomposition, leading to the accumulation of organic matter and the creation of large reservoirs of below-ground carbon (Parish et al. 2008; Joosten et al. 2012). Human activities have greatly reduced the areal extent of peatlands (Andersen et al. 2017; Harrison et al. 2020). As such, these ecosystems have become a key focus for nature-based solutions for climate change mitigation and ecological restoration (Tanneberger et al. 2021).

The processes of peatland degradation vary geographically due to differences in initial vegetation, hydrology and trajectories of land-use change. In tropical peat swamp forest systems, logging for valuable timber species and removal of forest cover leads to reductions in organic inputs, increased water loss via run-off and evaporation, and consequent drying, subsidence and erosion of the peat (Graham et al. 2017). These actions increase vulnerability to fires, which are long-lasting and hard to extinguish. Tropical peatland systems are drained by networks of canals and may subsequently be planted with monocultures, generating ongoing carbon losses and peat deterioration. High-latitude peatlands, particularly those typified by bryophyte and sedge plant communities, have been subject to peat-cutting for fuel and horticulture, which directly removes the vegetation and peat layer, and have been drained for agriculture, pasture and tree plantations (Andersen et al. 2017).

Natural regeneration in degraded peatland ecosystems is considered rare. Such recovery may be possible in selectively logged tropical sites in close proximity to natural forest with little fire disturbance (Blackham et al. 2014) albeit initially with an impoverished floral composition (Graham et al. 2017). More commonly, alteration to a site's hydrology is implicated in processes of both degradation and recovery in tropical, temperate and boreal biomes. "Rewetting" is often a first crucial step to initiate restoration (Table 1; Figure 5). In certain circumstances reducing grazing pressure and removing scrub vegetation to reduce evaporation rates can assist, but more often resource-intensive interventions are required: canals or ditches (originally installed to drain the peat) are dammed or infilled, to re-establish the environmental conditions suitable for endemic plant species (Joosten et al. 2012; Artz et al. 2019). Without rewetting, peatland is likely to undergo a transition to an alternative stable state. In the case of afforested peatlands, removal of non-native forest is a necessary early intervention, and continued removal of regrowth may be required. More involved surface reprofiling or contour bunding may be required to distribute and retain water in certain topographic settings and highly degraded sites to improve rewetting prospects (Payne et al. 2018).

Peat rewetting is not always straightforward. Drained peat is subject to compaction and subsidence (Joosten et al. 2012). Changes to structure, relief and porosity cause water to behave differently in a degraded system, resulting in greater seasonal fluctuations that affect recovering vegetation (Wösten et al. 2006). For example, in tropical peat forests, tree seedlings are unable to establish from seed and survive through the wet season when the peat may become submerged. Rewetting may be additionally challenging if deep fissures or pipes have developed, or where inflowing ground or surface water in fen ecosystems needs to be reconnected with their watershed (Chimner et al. 2017).

Revegetation of these systems is critical for stabilizing the peat surface, recovering plant matter for re-establishment of peat stocks, retaining moisture, and realizing the climate change mitigation potential of restored peatlands. Rewetting can lead to methane emissions which influence the greenhouse gas balance of peatlands in restoration (Levy et al. 2012). Generally, little natural regeneration occurs following peat-cutting (Chimner et al. 2017). Revegetation strategies in high latitude peatlands include seeding, plug-planting, brash spreading and propagation of mosses, along with removal of newly dominant vascular species (Artz et al. 2019). In degraded tropical peat forests, removal of ferns and ground vegetation alongside planting and maintaining tree seedlings of tolerant species is undertaken, but there is relatively little published evidence of degree of long-term efficacy in these schemes (van Eijk et al. 2009; Graham et al. 2017).

Although fires are rare in natural peatland ecosystems because of their hydrological conditions, degraded peatlands are susceptible to fire, with dead wood and dry peat acting as tinder fuel. Fire adversely affects naturally regenerating vegetation and plantings; in drought conditions (e.g. during strong ENSO events) these fires can be particularly devastating (Gaveau et al. 2014). Fires can smolder undetected under the surface and later reignite making them yet harder to control (Joosten et al. 2012). As such, fire prevention and control are critical interventions in peatland systems, particularly until the water table has been restored (Harrison et al. 2020).

The perception of peatlands as “wastelands” may reduce local support for rewetting; drained land and the drainage canals themselves provide access and it’s not uncommon for drain blocks to be removed (Joosten et al. 2012). Fires may arise accidentally, or may be initiated by people for further land clearance. As is often the case, local social consensus is critical in restoration outcomes. Full involvement of local communities in restoration planning are required, particularly when interventions are costly and stakes are high.

Conclusion: Assisting the recovery of ecosystems

Restoration practices across different types of ecosystems lie along a continuum rather than within discrete categories of passive vs. active forms. Further, most restoration projects employ a blend of different approaches, as emphasized in the recent modifications of the National Restoration Standards for the Practice of Ecological Restoration in Australia (Standards Reference Group, 2021). We advocate that policy and financial frameworks underpinning restoration recognize and place value on the breadth of approaches so that practitioners are able to apply common-sense approaches, rather than fit the mold of specific targets. Approaches strategically combining diverse degrees of intervention need to count as valid, and even preferred, restoration approaches (McDonald 2021). We focus attention on the need to mitigate or eliminate sources of human-caused degradation as the first step toward restoring ecosystems (Box 1). In some cases, doing so (which may require non-trivial efforts of persistence) may be the only intervention needed, apart from protecting the site from further damage or conversion.

There is nothing “passive” about promoting the self-recovery and self-organization of ecosystems.

Effective restoration interventions emerge from an understanding of nature’s intrinsic recovery potential, and overcoming obstacles that limit this potential (Box 1). Incentives for landowners are often needed to let natural ecosystems recover on their own, or with light or moderate assistance (Chazdon et al. 2020). Additional benefits from encouraging natural recovery of ecosystems include a significant reduction in implementation costs, the potential to reach larger spatial scales, favoring colonization of native locally-adapted genotypes, allowing natural processes to operate without human manipulation, and enhancing biodiversity through multi-species interactions and mutualisms during the self-recovery process.

In an era of global change, ecological restoration interventions must consider the need to build resilient ecosystems (Falk 2017). Restoration is not merely a “healing” process, but also requires preventive measures that strengthen resilience. Such measures can include: (1) allowing social–environmental systems to self-organize and adapt to novel biological, environmental, and social conditions (Messier et al. 2015); (2) where planting is needed, increasing the levels of diversity of species, functional types and genotypes planted, and increase functional redundancy to allow for adaptation and species turnover in response to climate extremes (Tuck et al. 2016); (3) assessing carefully the role of translocation and assisted migration in revegetation practices through improved understanding of risks and benefits in given ecosystem and geographical contexts; (4) supporting effective adaptive management by enhancing active involvement of local people in monitoring ecosystem restoration to promote more linkages between human and natural systems and to provide timely feedbacks (Messier et al. 2015); and (5) emphasizing connectivity at landscape and regional scales when planning locations for restoration, to permit movement and provide refuges for species. Using a stepwise, decision-tree approach to evaluate the potential for unassisted or lightly assisted recovery (Box 1) will enable scarce funds to be used most effectively, with positive outcomes for biodiversity and functions of naturally recovering ecosystems.

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Table 1. Continuum of interventions as applied to practices of ecological or ecosystem restoration in four ecosystem types. These are not discrete categories but reflect a continuous spectrum of restoration practices from unassisted (Natural or self-recovery) to intensively-assisted recovery. Within each assistance category, interventions are listed from less to more intensive.

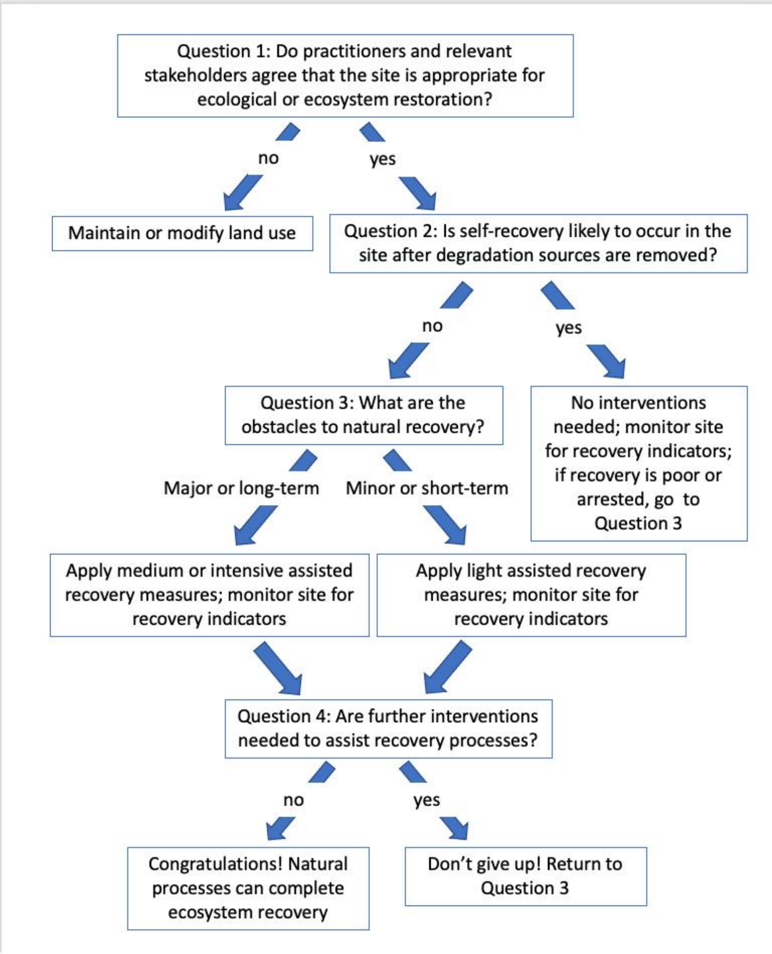
Type of ecosystem	**Unassisted (natural) recovery**	**Lightly-assisted recovery**	**Moderately-assisted recovery**	**Intensively-assisted recovery**
Forests	No interventions other than monitoring trajectory of recovery and prevent further site degradation	Exclusion of exotic grazers; protection from uncharacteristic fire or other disturbances and prescribed reintroduction of suitable fire regime weed control; protection from harvesting/hunting; enhancement of seed dispersal; pruning resprouted trees; enrichment planting; moderate	Stand thinning and controlled burning; local site preparation and direct seeding; local site preparation and partial or full tree planting; topsoil amendment and full tree planting	Terracing or other major landform modification; topsoil replacement; major hydrological modification; assisted migration

		post-fire erosion control		
Grasslands (dispersal limitation)	Monitoring unassisted colonization	Seed bank activation; assisted colonization; low diversity seed mixes; re-establish natural disturbance regime (e.g. prescribed fire)	Transfer of brush harvested seed or green hay; high-diversity seed mixes; plug planting	Turf or soil translocation
Grasslands (establishment limitation)	Re-establish natural or semi-natural disturbance regime (e.g. prescribed fire, grazing or hay making)	Pre-sowing ground disturbance; Hemiparasitic plants; mycorrhizal inoculation; nutrient cropping	Scrub removal; nutrient immobilization; invasive species control; restoration of suitable site hydrology	Soil inversion; topsoil removal

Rivers	Eliminate source of degradation, and monitor trajectory of recovery and prevent further site degradation	Weed control; selective thinning of riparian trees; fencing to prevent livestock access to channel; creating riparian buffer strips; soil conservation measures; sustainable drainage and natural flood risk management; renaturalization of flow regime	Local site preparation and tree planting; soft engineering to kickstart geomorphic processes; Removal or modification of hard engineering	Gravel addition; sculpting topographical features in floodplain; channel remeandering or reprofiling; new channel created
Peatlands	Natural recovery in lightly degraded (undrained) systems with proximal seed sources. Accept an alternative stable state of vegetation cover	Seedling release (e.g. fern removal); fire prevention and control; reducing evaporative water loss through scrub removal and reduced grazing pressure	Re-wetting through drain blocking to allow natural recovery; removal of non-native trees; revegetation (e.g. through plug planting, seeding, brash	Intensive site preparation including surface re-profiling or contour bunding

	without rewetting; monitor conditions and prevent further degradation and carbon losses, particularly run-off and peat layer erosion		spreading or planting native tree species)	

Box 1. Four steps to apply the intervention continuum to restoration decision-making



The first step in applying the continuum of interventions framework is to decide where restoration is relevant and possible, based on a wide range of social and ecological factors. This decision should be made by a team of stakeholders, practitioners, and scientific and technical advisors who understand the local context and who are accountable for their decisions and actions. The second step is to evaluate whether natural recovery can proceed, and whether it will fulfill the expected progression of outcomes over time. This step requires identifying and removing sources of degradation and then observing how the ecosystem responds. Often the observational step is skipped, as active interventions are assumed to be the default approach. If natural recovery occurs, the area under restoration should be considered as any other area undergoing restoration with respect to monitoring baseline conditions, evaluating outcomes, and adaptive management. This process requires an assessment of the factors that impede recovery, which can be based on local experience, traditional knowledge, or scientific research. Ecosystem-specific indicators of natural recovery potential can be developed and applied to inform this step. If natural recovery is not possible or will not deliver expected outcomes or rates of change, the third step is to determine which obstacles to natural recovery need to be overcome and in what temporal progression. In some cases, obstacles may be overcome with a "light," one-time intervention, whereas other cases may require intensive, repeated, or progressive interventions. In any case, all interventions will require monitoring to assess recovery responses and to determine if follow-up actions are needed. The fourth step in decision-making involves a determination of the condition or stage when ecosystem recovery can proceed without further interventions. This decision is based on monitoring data and requires a set of indicators distinct from those used to signal the potential for initiation of self-recovery. Depending on the circumstances, this stage can be at a relatively early or a late phase of ecosystem recovery.

Figure Legends

Figure 1. Continuum of interventions as applied to forest restoration. See Table 1 for application of the framework to additional ecosystems. Restoration may require one-time or repeated interventions as illustrated in the decision tree in Figure 2. Most restoration projects will employ a combination of approaches across this spectrum.

Figure 2. Examples of unassisted post-disturbance forest regeneration. (A) and (B) Ponderosa pine (*Pinus ponderosa*) recruitment three years post-thinning treatment, Monument Canyon Research Natural Area, Santa Fe National Forest, Jemez Mountains, New Mexico. Seedling and sapling density 10^7 stems ha^{-1}. (C) Wave-front tree recruitment into burned patch from the 2000 Jasper Fire, Black Hills, South Dakota (photo courtesy Paula Fornwalt, Rocky Mountain Research Station, US Forest Service. (D) Aspen and conifer tree regeneration in 2017 following the 2000 Hi Meadow Fire, CO (photo courtesy Robin Chazdon).

Figure 3. Restoration interventions in grasslands. Natural recovery: (A) Reintroduced bison grazing in restored tallgrass prairie (Nachusa Grasslands, Illinois, USA) (Photo – © Dee Hudson, TNC). Lightly assisted recovery: (B) Bare ground creation by harrowing prior to target species sowing (Bedfordshire, UK) (Photo – © Lucy Hulmes, UKCEH). Moderately assisted recovery: (C) Nutrient immobilization by sawdust application (Movelier, Switzerland) (Photo – © René Eschen, CABI). Moderately assisted recovery: (D) Green hay spreading using a manure spreader (Buckinghamshire, UK) (Photo – © John Redhead, UKCEH). Moderately assisted recovery: Plug planting of target species involving (E) extraction of a soil core the size of the seedling plug, followed by (F) planting and watering (Bedfordshire, UK) (Photos – © Lucy Hulmes,

UKCEH). Moderately assisted recovery: (G) Fire management of Brazilian Cerrado to control the invasive grass *Melinis minutiflora* (Itirapina, São Paulo, Brazil) (Photo - © Alessandra Fidelis, Universidade Estadual Paulista). (H) Intensively assisted recovery: Topsoil inversion to bury nutrient-rich topsoil and replace it with nutrient-poor subsoil to create suitable soil conditions for restoration (Norfolk, UK) (Photo – © Damian Young, Plantlife). Intensively assisted recovery: (I) and (J) Blocks of turf cut from chalk grassland destroyed by construction are relocated (East Sussex, UK) (Photo (I) - © Dawn Brickwood, WMP & S (www.highwealdlandscapetrust.org) , photo (J) - Ted Chapman, © RBG Kew).

Figure 4. Restoration interventions in rivers. Natural recovery: (A) An over-widened low-energy chalk river recovers via (B) natural vegetation establishment and geomorphic processes in the River Frome (Dorset, UK) (Photo – R. Grabowski). Moderately assisted recovery using willow spilling showing how (C) heavy shading inhibits natural stabilization of marginal sediment by aquatic vegetation to (D) narrow the channel of the low-energy River Chess (Buckinghamshire, UK) (Photo – RRC). Moderately assisted recovery: (E) Upstream facing trees placed into the banks of the lowland River Avon to increase hydraulic variability and mobilize the gravel bed (Wiltshire, UK) (Photo – Natural England). Intensively assisted recovery: (F) The over-deepened and historically straightened Swindale Beck (England) was (G) remeandered and reconnected to the floodplain by bank reprofiling and reuse of coarse sediment in the channel (Photos - Lee Schofield RSPB).

Figure 5. Restoration interventions in peatland ecosystems. (A) Bare peat pan in Nidderdale, Yorkshire, UK, revegetated by heather brashing, seeding with dwarf shrubs and grass mix, and

planting with cotton grass (photo credit Jenny Sharman, Yorkshire Peat Partnership). (B) Gully blocking with coir rolls to rewet and reduce peat erosion on a site in the Yorkshire Dales, delivered by Yorkshire Wildlife Trust through the Pennine Peat LIFE project and Yorkshire Peat Partnership, Yorkshire, UK (photo credit Katie Aspray, Environment Agency). (C) Canal blocking to rewet degraded and burnt tropical peatswamp forest, Kalimantan, Indonesian Borneo (photo credit Chris Evans, UK Centre for Ecology & Hydrology). (D, E) Early-stage and post restoration photographs at South Corries, Scotland, UK involving removal of non-native forest cover, trench back-filling and ground smoothing and brash mats (photo credits Ed Turner, Forestry and Land Scotland).

Figure 1

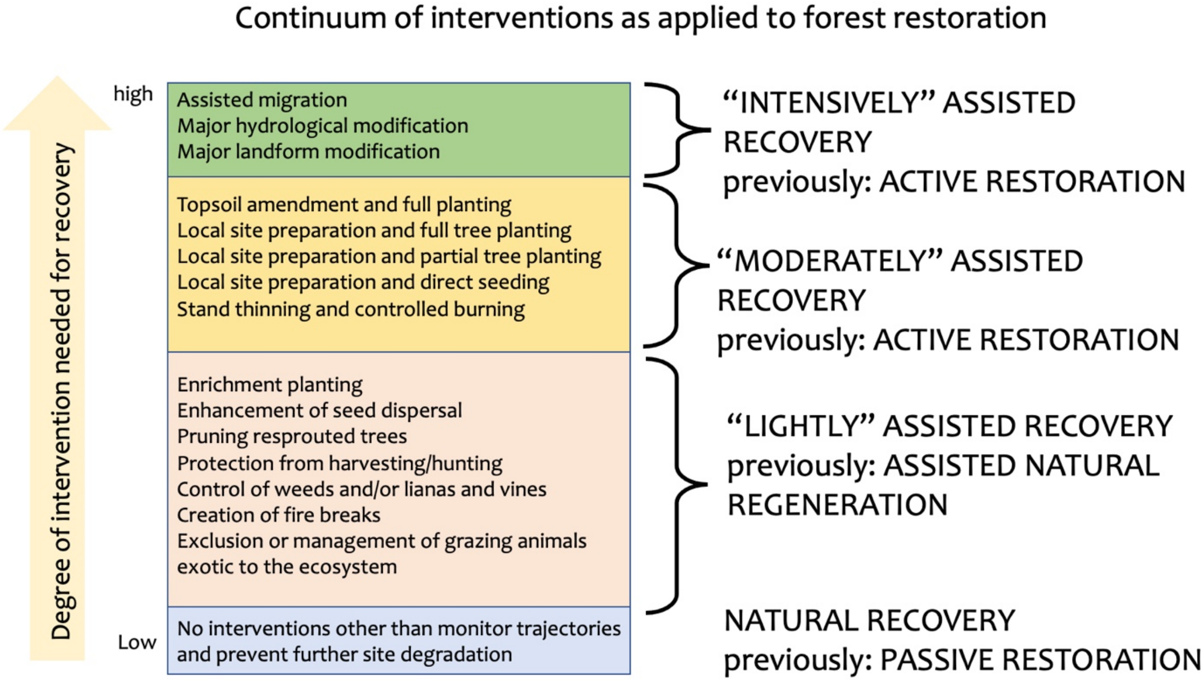

Continuum of interventions as applied to forest restoration
Degree of intervention needed for recovery
high
Low
Assisted migration
Major hydrological modification
Major landform modification
Topsoil amendment and full planting
Local site preparation and full tree planting
Local site preparation and partial tree planting
Local site preparation and direct seeding
Stand thinning and controlled burning
Enrichment planting
Enhancement of seed dispersal
Pruning resprouted trees
Protection from harvesting/hunting
Control of weeds and/or lianas and vines
Creation of fire breaks
Exclusion or management of grazing animals exotic to the ecosystem
No interventions other than monitor trajectories and prevent further site degradation
"INTENSIVELY" ASSISTED RECOVERY previously: ACTIVE RESTORATION
"MODERATELY" ASSISTED RECOVERY previously: ACTIVE RESTORATION
"LIGHTLY" ASSISTED RECOVERY previously: ASSISTED NATURAL REGENERATION
NATURAL RECOVERY previously: PASSIVE RESTORATION

Figure 2

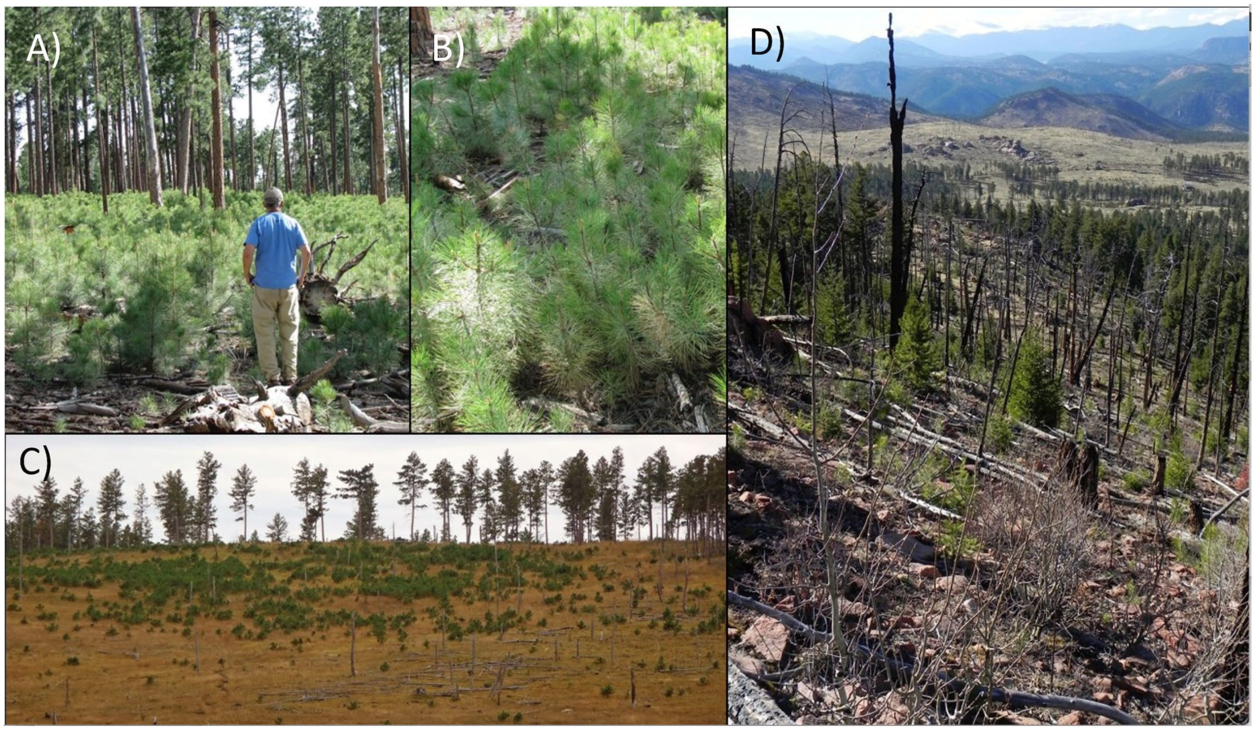
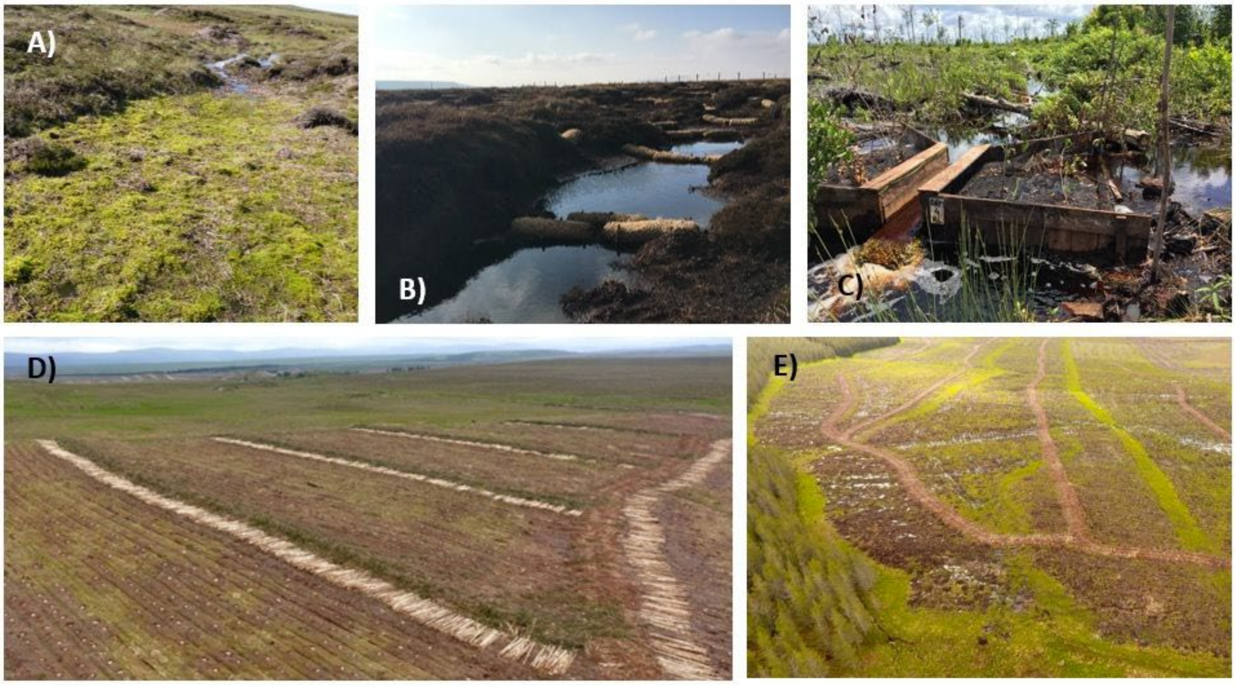


Figure 3

Figure 4

Figure 5



The intervention continuum in restoration ecology: rethinking the active-passive dichotomy

Chazdon, Robin L.

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