Botanical Sciences 100 (Special Issue): S218-S244. 2022
DOI: 10.17129/botsci.3149

Received: March 16, 2022, Accepted: July 23, 2022
On line first: August 31, 2022

Ecological Restoration / Restauración Ecológica

The challenge of participatory restoration in rural areas
El reto de la restauración participativa en áreas rurales

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Abstract
Restoration is a prominent field of research and of restoration projects that seek to recover degraded and dysfunctional ecosystems and the services they provide. Humanity's environmental crisis has increased awareness of the urgent need to conserve ecosystems and their biodiversity. Many countries and international organizations have set ambitious plans and restoration targets. This paper emphasizes on current themes such as landscape restoration, invasive species, novel ecosystems, and the necessary involvement of local communities in ecological restoration. It is focused mainly on tropical forest ecosystems. Another aim of this paper is a review of the results obtained in diverse restoration practices that concentrate on inducing secondary succession processes in tropical forests. It draws heavily on case studies from Mexico. Members of society should play an active role in restoration planning and implementation. Social participation is central to the success and sustainability of restoration projects. Traditional ecological knowledge is essential in many projects, and there should be careful consideration of the ethics involved. In the coming years, we will probably see a surge in the unassisted revegetation and reforestation of many abandoned rural areas making the understanding and managing of these restoration processes necessary and crucial. Finally, a set of guidelines that view restoration as a long-term social and ecological process is given.
Key words: Involvement, Landscape restoration, Tropical forests, Society

Resumen
La restauración ecológica es un campo destacado de investigación y de proyectos de restauración en campo que buscan recuperar ecosistemas degradados y disfuncionales y los servicios que proporcionan. La crisis ambiental que enfrenta la humanidad ha aumentado la conciencia sobre la necesidad urgente de conservar los ecosistemas y su biodiversidad. Muchos países y organizaciones internacionales han establecido planes ambiciosos y objetivos de restauración. Este documento se centra principalmente en los ecosistemas de bosques tropicales y hace énfasis en temas actuales como la restauración del paisaje, las especies invasoras, los ecosistemas emergentes y la necesaria participación de las comunidades locales en la restauración ecológica. Otro objetivo de este artículo es hacer una revisión de los resultados obtenidos en diversas prácticas de restauración que se enfocan en inducir la sucesión secundaria del bosque tropical; para ello, se utilizan muchos ejemplos de México. Los miembros de la sociedad, sobre todo las comunidades locales, deben desempeñar un papel activo en la planificación e instrumentación de la restauración. La participación social es fundamental para el éxito y la sostenibilidad de estos proyectos. El conocimiento ecológico tradicional es esencial en muchos proyectos y debe haber una cuidadosa consideración de la ética involucrada. En los próximos años, probablemente veremos un aumento en la revegetación y reforestación natural de muchas áreas rurales abandonadas. Ello hace necesario y crucial el entender y manejar estos procesos de restauración. Finalmente, se da un conjunto de lineamientos que contemplan la restauración como un proceso social y ecológico a largo plazo.
Palabras clave: Bosque tropical, Participación, Restauración del paisaje, Sociedad.

Restoration is a fast-growing and increasingly relevant field of interest. Research on restoration ecology and ecological restoration will likely continue to advance rapidly in the future. Over just 15 years (1990-2004), 5 % of the ecology articles published worldwide were on restoration (Young *et al.* 2005). Right now, the United States of America has the highest number of papers in this field, China is in second place, followed by Australia, the United Kingdom, Germany, Canada, France, Spain, Brazil, the Netherlands, Italy, New Zealand, whereas Mexico occupies the 13th place (Guan *et al.* 2019, López-Barrera *et al.* 2017).

Ecological restoration has become more prominent in the academic literature, but empirical studies on the outcomes of restoration have lagged behind (Burke & Mitchell 2007, Cabin *et al*. 2010). The number of empirical papers has grown considerably but the geographical distribution of the research is still heavily biased toward a few well-developed countries (Guan *et al.* 2019).

Restoration always takes place within a system of governance that brings together numerous participants that regulate their relationships (Stanturf *et al.* 2014). There is a need to understand the ecological dimensions, but sociological and economic aspects are also crucial (Gann *et al.* 2019). Ecosystem restoration is advancing fast worldwide, but restoration projects recurrently fall short of addressing the human dimension, primarily through the engagement of local people (Ceccon *et al.* 2020). Societal values propel restoration and because of this human component, endeavors to put into words a universal definition of restoration as its many facets continue to generate discussion and evade consensus (Stanturf *et al*. 2014). Martin (2017) discusses several definitions of ecological restoration. He argues that ecological restoration has progressed into a social and scientific concept; these existing definitions suggest our views about what ecological restoration does, but not why we do it. He defines it as:

> "the process of assisting the recovery of a degraded, damaged, or destroyed ecosystem to reflect values regarded as inherent in the ecosystem and to provide goods and services that people value." (Martin 2017, p. 670).

In this definition, he refers to the multiple ways that nature is valuable and maintains us. Mexico and many Latin American countries urgently need to recover their native vegetation structure, biodiversity, and ecosystem function while sustaining the productive activities of rural inhabitants and the valuable ecosystem services they offer. This paper emphasizes on some themes that are currently important in restoration ecology such as landscape restoration, invasive species, novel ecosystems and the necessary involvement of local communities in ecological restoration. It is focused mainly on tropical forest ecosystems, but many of the ideas put forth come from work on other ecosystems. Many international agencies and national governments have committed themselves to restoring 15 % of globally degraded ecosystems. Rural migration towards the cities has left many areas where secondary succession occurs. Therefore, another aim of this paper is a review of the results obtained in diverse restoration practices that focus on accelerating the successional tropical forest process. This type of strategy should involve local communities.

Current advances

Worldwide, there is a growing awareness of the urgent need to conserve the natural areas that still remain on our planet; the world's biodiversity needs to be preserved and our ecosystems have to recover their functions and ability to provide ecosystem services. Several international efforts have sprang converging on the need to restore degraded ecosystems and have proposed ambitious goals (Méndez-Toribio *et al.* 2021): The Aichi Target 15 of the Convention on Biological Diversity (www.cbd.int/sp/targets), restoring 15 % of degraded ecosystems, the Bonn Challenge (www.bonnchallenge.org), later supported and broadened by the New York Declaration on Forests at the 2014 UN Climate Summit (forestdeclaration.org/about), the Zero Net Land Degradation (United Nations Convention to Combat Desertification), the Initiative 20x20 for Latin America (https://initiative20x20.org/restoring-latin-americas-landscapes), the Sustainable Development Goals (www.un.org/sustainabledevelopment/sustainable-development-goals), the United Nations General Assembly declaration that 2021 to 2030 be the Decade on Ecosystem Restoration (www.decadeon-restoration.org), and the Ocean Decade 2021-2030 (www.oceandecade.org). COP 26 ended up falling woefully short of the proposed targets. "It is an important step but is not enough," said United Nations Secretary General António Guterres in his closing remarks at the conference. "Our fragile planet is hanging by a thread. We are still knocking on the door of climate catastrophe. It is time to go into emergency mode —or our chance of reaching net-zero will itself be zero." (www.unep.org/news-and-stories/story/cop26-ends-agreement-falls-short-climate-action). In recent years, many international organizations have embraced restoration within their policies and international agreements, and have set ambitious plans and restoration targets (Higgs *et al.* 2018, Méndez-Toribio *et al.* 2021). Globally, two billion hectares of forest need to be restored (Stanturf *et al.* 2014), with a functioning landscape that contemplates the livelihood needs of local communities and provides ecosystem services (Lamb *et al*. 2012). Ecological restoration, when executed effectively and sustainably, helps protect biodiversity, improves conditions for human health and well-being, facilitates an increase in food and water security, is vital for delivering goods, services, and economic prosperity, and is the core for supporting climate change mitigation, resilience, and adaptation (Gann *et al.* 2019).

The Society for Ecological Restoration (SER) has introduced a series of policies to guide practice (Gann *et al.* 2019, see Méndez-Toribio *et al.* 2021), which help practitioners and have induced discussions on ecological restoration. When ecological restoration includes conservation and sustainable use, it can become the link that moves local, regional, and global environmental conditions from a state of continual degradation to one of net improvement (Gann *et al.* 2019). Higgs *et al.* (2018) advise a flexible, open approach to restoration practices to encourage the rapid upscaling of investment in restoration, the mitigation of climate change, attention to human needs, to address scientific uncertainties, and to put locally appropriate innovations into practice.

Ecological restoration is considered the "acid test" of our ecological understanding as it provides experimental settings for testing ecological theory. It has brought new focus to existing ecological theory, encouraged a handful of novel ecological ideas, and increased interest in matters of restoration at the landscape and ecosystem levels (Young *et al.* 2005). Harris et al. (2006) examine the potential repercussions of global climate change for ecological restoration. They discuss prevailing conservation strategies built on particular species (*i.e.*, Special Scientific Interest for Wildlife Protection in the United Kingdom). They believe these spots will be more precarious and less resilient and diminish or exclude the ability of the species and ecosystem to adapt to changes in the biophysical conditions. In a world of quickly changing climate regimes, we require a broader consideration of ecosystem functions and processes. A defining characteristic of functional restoration is its effort on the sustainability of multi-scale ecosystem processes, including hydrologic cycles, food web interactions, ecosystem productivity, rather than particular structures and compositions (Stanturf *et al.* 2014).

> "Hence, an increasing emphasis will be on proper functioning condition of a site -ecological integrity - and to a lesser extent on nudging a site back to historical conditions based on species. In general, process, not structure, will prevail." (Harris *et al.* 2006, p. 174).

Despite being a young science, there have been numerous papers with reviews (Table S1). These reviews reveal numerous themes in ecological restoration, though many more are needed to allow both researchers and practitioners to detect tendencies, gaps in methodologies, successful experiences, among others. Callaham Jr. *et al.* (2008) pointed out that research in terrestrial restoration ecology has been dominated by the engineering and botanical sciences, and there is still a gap between ecological engineering and ecological restoration (Aronson *et al.* 2016).

Our experience in ecological restoration is still limited. Developing and bolstering an intrinsic connection between the science of restoration ecology and the practice of ecological restoration is vital. The difficulty arises from the polarization between conceptual restoration (restoration ecology) and practical restoration (ecological restoration), with each having functioned to a certain degree in isolation from the other (Burke & Mitchell 2007, Cabin *et al.* 2010).

Landscape restoration

Historic land use practices have drastically transformed landscapes across all scales, homogenizing them and limiting opportunities for both humans and wildlife. Landscapes are multifunctional, and people place multiple, often conflicting, demands on them. There is a need for multifunctional landscapes that also provide food security, a means of earning a living, maintain species and ecological functions, and that fulfill cultural, aesthetic, and recreational needs (O'Farrell & Anderson 2010). In 2005, Higgs (2005) stated that ecological restoration would ideally include a set of restoration practices that also included the relevant human and natural sciences, politics, technologies, economic factors, and cultural dimensions. Thus, successful restoration requires a comprehensive view that includes historical, social, cultural, political, aesthetic, economic and moral attributes, and also takes into consideration how restoration efforts relate to patterns of resource use and the values and activities important to society. It should be based on traditional or local knowledge as well as a scientific understanding of previous conditions (Uprety *et al*. 2012). The extent to which natural ecosystems are the outcome of human transformation is variable, but it is recognized that widespread changes have occurred and have been continued as traditional practices that are comparable to natural disturbances. In sustaining native biodiversity, traditional management practices should be encouraged as an indispensable part of ecosystem integrity (Gann *et al*. 2019).

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) promotes *land restoration*, which includes activities such as restoring agricultural productivity, adopting agricultural best practices, and other sustainable utilization activities. Landscape restoration, on the other hand, involves practices based on the principles of both landscape ecology and landscape sustainability science (Frazier *et al.* 2019), in which a landscape is seen as a social-ecological system. Consistent with the definition of landscape sustainability (Wu 2013), landscape restoration can be approached as a planned process that tries to regain landscape-level ecological integrity and the capability of a landscape to supply long-term, landscape-specific ecosystem services crucial to improving human well-being. Simply put, it is impossible to exclude humans and their impacts from the landscapes they live on. Other attempts at large-scale restoration embrace the concept of Sustainable Multifunctional Landscapes, which are "landscapes created and managed to integrate human production and landscape use into the ecological fabric of a landscape maintaining critical ecosystem function, service flows, and biodiversity retention" (O'Farrell & Anderson 2010).

To restore functional ecosystems, landscape-level approaches are needed. Regarding ecosystem functions in a restoration project, the practitioner must take into account the location of the project on the landscape —its boundaries, its connections or lack thereof to adjoining ecosystems, and its gains and losses of materials and energy from its physical surroundings (Ehrenfeld & Toth 1997). In their review of the inclusion of ecosystem functions in restoration projects, Kollmann *et al.* (2016) found that 26 % focused on nutrient cycling, 18 % on productivity, 16 % on water dynamics, 14 % on geomorphological processes, 10 % on carbon sequestration, 6 % on decomposition, and 6 % on trophic interactions.

Thus, the landscape is the stage for biological and cultural diversity. Reaction to disturbances translate into small or large variations in the structure and functioning of the landscape that influence its resilience. These variations also remain in the landscape, so we can speak of the landscape's memory and thus, the landscape is a natural and human construct that has a history and memory (Guevara 2016). When ecosystems within landscapes are degraded, they lose the ability to provide habitats for biodiversity, and to provide environmental services, a pressing matter. In this context, the concept of landscape restoration (Figure 1) has emerged, *i.e.*, the process of recovering the capability of a landscape to supply in a consistent way and in the long-term, the indispensable environmental services it provides for the improvement of human well-being (López Barrera & Bonilla Moheno 2022).

Restoration strategies

The relative youth of the discipline relative to the timescale on which ecological processes occur is partly responsible for the uncertainty regarding the effectiveness of restoration programs (Wortley *et al.* 2013). Furthermore, there is some debate about how to measure success and what to monitor (Ruiz-Jaen & Aide 2005, Herrick et al. 2006, Wortley *et al.* 2013). Restoration projects are unique, and goals and activities differ depending on the circumstances, making success and monitoring central themes (see Table S1)

Frequently, different types of activities are grouped under the concept of restoration. Gann *et al.* (2019) state there is an assortment of restorative activities that can be recognized as a continuum, keeping in mind that they are quite distinct (Figure 2). The continuum highlights interconnections among them and acknowledges that the particular

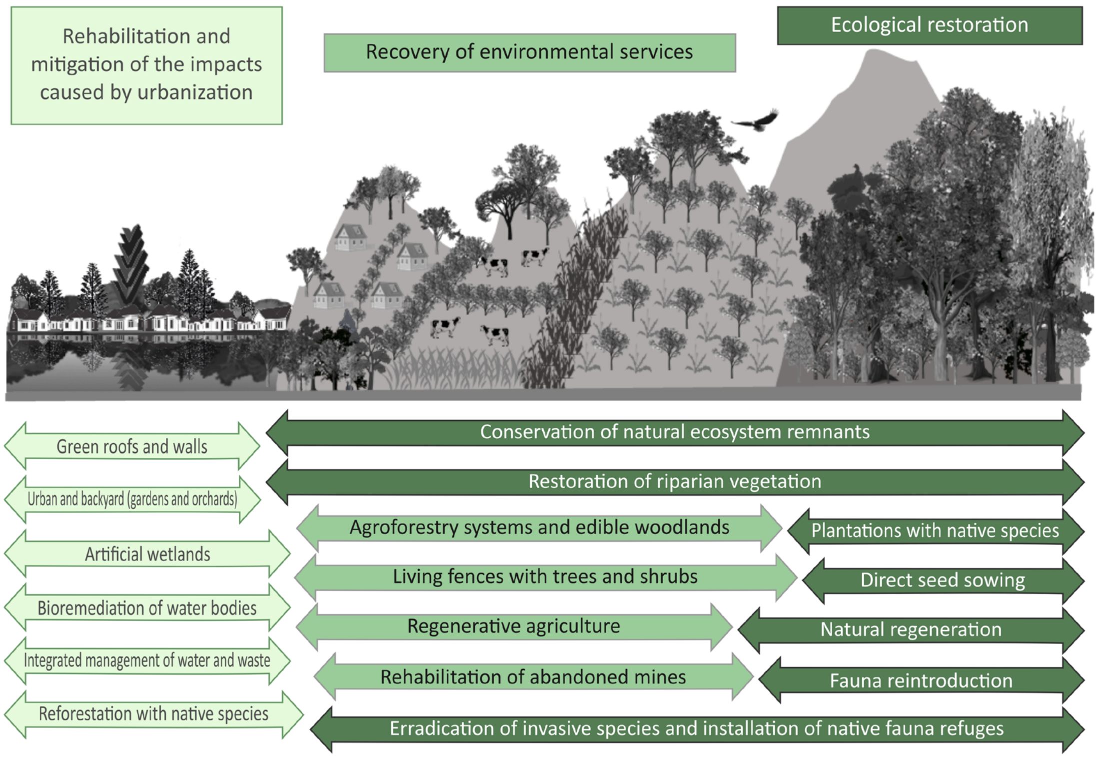

Figure 1. Landscape restoration indicating the areas where the rehabilitation and mitigation of urbanization impact take place, the types of productive land where environmental services are being recovered, and areas where restoration ecology takes place (From López Barrera & Bonilla Moheno 2022).

characteristics of the locality lined up for restoration activities prescribe the actions best suited for different landscape units. As one moves from left to right on the continuum, ecological health and biodiversity result, and the quality and quantity of ecosystem services multiplies (Gann *et al.* 2019). Table 1 describes these strategies (left column).

Stanturf *et al.* (2014) argue that extending the scope of restoration beyond the site will entail the incorporation of the restoration actions with the other land uses; it will have to adapt the various management goals of multiple title holders of the land and integrate human livelihood needs (Lamb *et al.* 2012). Stanturf *et al.* (2014) describe four restoration strategies: rehabilitation, reconstruction, reclamation, and replacement. They emphasize the objectives, strategies and methods used to obtain results, giving numerous examples. Moving from rehabilitation to reconstruction to reclamation stumbles upon increasing levels of degradation, loss of productivity, dysfunction, and decreases in sustainability and services. The necessary activities in the face of degraded, damaged, or destroyed ecosystems set restoration apart. They are described in Table 1 (right column).

The categories used are not entirely equivalent. The strategies described by Gann *et al*. (2019) are a continuum of restorative activities that steer towards the full recovery of an ecosystem. The strategies described by Stanturf *et al.* (2014) refer to the process of deciding restoration objectives, conditioned by the scale, social context, and level of restoration desired. The latter are method-oriented and presented as available tools (restoration toolbox with many techniques and tools), including appropriate materials and methods for altering composition, structure, and processes.

Well-defined expectations have long been accepted as a critical element of a restoration project. These authors give us a variety of activities that directly or indirectly support or achieve at least some recovery of ecosystem features that have been lost or compromised. They represent an instrument for change, and the anticipated endpoint that orients activities depending on the level of degradation, dysfunction, reduced productivity, and diminishing services and sustainability (Gann *et al.* 2009, Stanturf *et al.* 2014).

Importance of invasive species in restoration

Invasive species are a paramount element of global change; they are furthering biodiversity loss, ecosystem degradation, and diminishing ecosystem services in the world (Pyšek & Richardson 2010). In a recent paper, Pyšek *et al.* (2020) wrote a scientist's warning on invasive alien species that are the consequence of our connected, global world and dramatic increase in population. The number of invasive alien species is escalating and their impact on biodiversity and ecosystems is increasing. Invasive plant species can obstruct the establishment and growth of native plants and affect several ecosystem properties, *i.e.*, nutrient cycling, fire regimes, soil cover, and hydrology. The control of invasive plants is therefore a necessary yet frequently expensive, step on the road to restoring an ecosystem (Weidlich *et al.* 2020). Table S1 includes a synthesis of literature reviews that deal with the invasive plants' impacts and their control in restoration contexts. Two conceptual frameworks are of interest in restoration studies in ecosystems dominated by invasive plants. Doren *et al.* (2009) developed a conceptual ecological model for invasive exotics to help understand their function in ecosystem ecology and their effects on restoration activities in the Everglades. The model offers groups of characteristics, processes, and hypothesized causal relationships to take into account when considering the impacts or potential effects of these exotic invasive species and how restoration efforts will affect these features and processes. Funk *et al.* (2008) worked on concepts concerning the assemblage of plant communities that can be utilized to strengthen resistance to invasion in restored communities.

There is an ongoing debate in the field of invasion biology and on the impact of invasive alien species. Some are of enormous economic importance to the well-being of people, and researchers in the humanities and social sciences are participating in discussions on this aspect of the issue. Among them, Davis (2020) emphasizes that several factors are creating ecologically novel environments and calls for the presence of different perspectives and voices. Vaz *et al.* (2017) analyzed interdisciplinarity in invasion science papers and found that 92.4 % of publications with interdisciplinary participation deal with ecological questions, and only 4.4 and 3.2 % on social and social-ecological questions, respectively. Therefore, it is desirable to include an interdisciplinary perspective in restoration projects.

Emerging or novel ecosystems

In 2006, Hobbs *et al.* (2006) wrote about the emergence of the concept of "novel ecosystems" and this idea is reshaping the field of ecological restoration, or at least making us think about local situations and alternatives. These ecosystems develop from biotic reactions to human generated abiotic conditions, such as increased soil fertility, land degradation, and the establishment of invasive species (Hobbs *et al.* 2006). The concept is still subject to widespread debate (Marris *et al.* 2013, Aronson *et al.* 2014, among others). Marris *et al.* (2013) argue that the novel ecosystem concept is an effective transitional concept. They wrote:

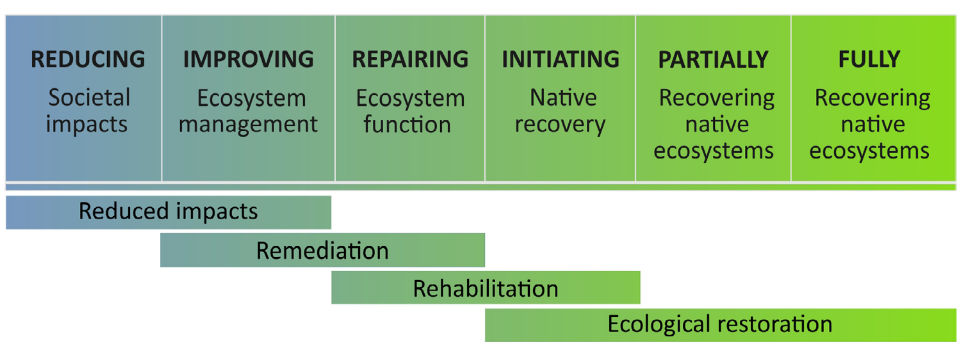

Figure 2. The restoration continuum embraces a set of interventions that can enhance environmental conditions and reverse ecosystem deterioration and landscape fragmentation. From left to right on the continuum, both ecological health and biodiversity increase, as do the quality and quantity of ecosystem services (Redrawn from Gann *et al*. 2019).

Table 1. Comparison of restoration strategies.

Gann *et al.* (2019)	**Stanturf *et al.* (2014)**
Reduce societal impact, *i.e.*, consuming natural and manufactured products in less damaging ways, and utilize ecosystem services across all sectors. On the production side, intensifying regulation in many territories of the world is occasioning more ecologically informed farming, fisheries, forestry, and mining methodologies. On the consumption side, an amalgamation of regulation and increasing social expectation is modifying some manufacturing practices and social behaviors, mainly in urban areas. These actions are restorative because they diminish the causes and current effects of degradation, increase the potential for ecosystem recovery, and encourage a transition to sustainability. It includes improving ecosystem management (see Figure 2).	
Remediation, *i.e.*, of polluted and contaminated areas. When rehabilitation is used for mined lands or post-industrial sites, it is called reclamation. It includes improving ecosystem management and repairing ecosystem function (see Figure 2).	**Reclamation** applies to severely degraded land usually bereft of vegetation, often resulting from belowground resource extraction, *i.e.*, mining. Sometimes non-native species are used as nurse plants (replacement) to assist the proliferation of native vegetation.
Rehabilitation, *i.e.*, including areas used for production or human settlement where the target is not to recuperate the native ecosystem, but rather to reestablish a level of ecosystem functioning for the improved and future provision of ecosystem services, hypothetically obtained from nonnative ecosystems. Its goal is to restore ecosystem functioning rather than the biodiversity and integrity of a selected native reference ecosystem. Rehabilitation projects getting some enhancement of ecological conditions can later be intended for ecological restoration. It includes repairing ecosystem function and initiating ecosystem recovery (see Figure 2).	**Rehabilitation applies** to restoring the coveted species composition, structure, or processes to a degraded ecosystem. Two specific approaches to rehabilitation are: conversion (seems to apply to comprehensive removal of an existing overstory and substitution with other species, *i.e.*, a degraded forest, cleared or burned, and requiring desired species be converted through agroforestry) and transformation (an extended process of partial subtractions and species replacement, *i.e.*, in this same degraded forest, underplanting or natural regeneration).
	Reconstruction refers to restoring native plant communities on land under other resource uses not long ago, such as crop production or pasture. For example, a deforested abandoned agricultural land, it necessitates afforestation and planting. Reconstruction may look as if beginning with a blank template, but prior land use frequently leaves a legacy of degraded soil and competing vegetation. Nevertheless, reconstruction allows the opportunity to restore ecosystems with simple or complex structures, consisting of an overstory with one or many species and an understory that results from recolonization or planting and seeding.

Gann *et al.* (2019)	Stanturf *et al.* (2014)
Ecological restoration aims to significantly recover the native biota and ecosystem functions. The reference models employed for ecological restoration projects are based on native ecosystems, among them many traditional cultural ecosystems. It can take place in urban, agricultural, and industrial landscapes. It includes partially recovering native ecosystems and their total recovery (see Figure 2).	
	Replacement of species (or their locally-adapted genotypes) with new species (or new genotypes) as a reaction to climate change.

> "Whatever the past, today we live in a biosphere governed by human legacy and design. Humans have altered everything, and there is no going back. Our hope is that the novel ecosystems concept will help us understand this reality. Time will tell how useful we find the term, and for how long, as we learn to be conscious managers to our rapidly changing planet." (Marris *et al.* 2013, p. 348).

Because of all these changes, some authors think that historical restoration goals are likely to be unsustainable in the coming decades (Seastedt *et al.* 2008, Jackson & Hobbs 2009). In order for the potential of ecological restoration to be fulfilled as a key tool in managing the current challenge of climate change, conventional approaches that rely exclusively on historical references may not be effective. They must be set against the possibility that restoring these historic ecosystems is not likely to be simple, or even probable, under the changed biophysical conditions of the future (Harris *et al.* 2006). Therefore, ecological restoration efforts should seek to conserve and restore historical ecosystems where this approach is viable, while simultaneously preparing to design or steer emerging novel ecosystems to ensure that they continue to provide ecological goods and services (Jackson & Hobbs 2009, Uprety *et al.* 2012). Timpane-Padgham *et al.* (2017) suggest including resilience as an unambiguous planning target that could improve the success of restoration projects.

The transportation of plants and animals by humans during colonization has led to the exchange of species among continents throughout history. Many essential and economically valuable crops -ranging from grains to trees, fish and livestock- now grow on a continent far from where they originated. There are several interesting examples that can be considered emerging ecosystems. The first regards the many invasive grass species associated with cattle ranching in terrestrial and wetland habitats. Globally, new sets of introduced and native plant and animal species have converted rangelands into novel ecosystems (Hobbs *et al.* 2006, Belnap *et al.* 2012). Species have been intentionally introduced to wetlands and rangelands because their functions are beneficial to humans (*e.g.*, erosion control, shade, forage). In rangelands, novel ecosystems frequently result from management-induced variations imposed on native plant communities, thus creating opportunities for invasion or expanding the density (or range) of alien and native species (Milton *et al.* 2007). There are many examples of how these changes arrest succession in different types of ecosystems: African grasses (mainly *Panicum clandestinum*) were introduced for cattle ranching and have caused the savannization of the Andean landscape; they have arrested succession and encroached upon the tropical montane forests toward steeper slopes and higher limits (Sarmiento 1997); exotic grasses hinder the recovery of native communities on former agricultural land in the Inland Pampa, Argentina (Tognetti *et al.* 2010); also, exotic grasses have dominated pastures in tropical forests located in the tropical Andes and have also arrested succession (Rojas-Botero *et al.* 2020). In tropical wetlands small environmental changes in hydrology favour the expansion of exotic grass invaders (López-Rosas & Moreno-Casasola 2012) but also of native grasses and can arrest succession (Vázquez-

Benavides *et al.* 2020). Thus, many of the changes brought about by invasive exotic species create new communities with different structures and compositions, making restoration a more difficult goal.

Some authors have taken a more pragmatic approach toward these new ecosystems. Belnap *et al.* (2012) examined a wide range of novel ecosystems, created by the intentional and unintentional introduction of non-native species and land-use-facilitated spread of native species in Africa, Australia, and North America. The widespread presence of this problem has made some authors suggest that when a species threatens the regulating and supporting services provided by the ecosystem, there is a strong case for eradicating that species or altering the mechanisms that enhance its success (Seastedt *et al.* 2008). Belnap *et al.* (2012) propose a system that helps make a decision on actions towards particular invasive species. If a species does not threaten the services or only does so in limited areas, or if it threatens the provision of ecological or cultural services, a decision can be made to keep the species based on cost-benefit analyses and conflict–resolution processes (*e.g*., stakeholder workshops) (Belnap *et al.* 2012), or managed to deliver specific ecosystem services (*e.g.*, forage production, carbon sequestration) (Tognetti et al. 2010).

An interesting example of novel ecosystems are shade coffee plantations, currently a common crop in many Latin American countries, some still in production and others abandoned. Many ecological studies have been undertaken on these plantations. Oliveira-Neto *et al.* (2017) found an unusual combination of species documented for the first time for a semideciduous seasonal forest, as well as the naturalization of exotic species (*Coffea arabica, Eryobotria japonica, Morus nigra*, etc.). They concluded that this area can be considered a novel ecosystem *sensu* Hobbs *et al.* (2006).

Shade coffee plantations, these novel ecosystems, represent a forest management alternative that can maintain vegetation structure (Alvarez-Alvarez *et al.* 2020), with levels of species richness similar to those of coffee agroforests (Badari *et al.* 2020), can act as a biodiversity-friendly matrix that offers complementary or supplementary habitat to resident bird species in a biodiversity hotspot in Colombia (Sánchez-Clavijo *et al.* 2019), and fruit production by *Prunus integrifolia,* a tree that dominates the shade coffee areas, feeds Andean night monkeys (*Aotus lemurinus*) (Guzmán *et al.* 2016).

In Puerto Rico, Lugo & Helmer (2004) studied new forests in different upland and wetland forests, with many alien tree species. They are highly fragmented, operate as refugia for native organisms, and have species richness and structural features comparable to those of native stands of similar age. Mascaro *et al.* (2012) worked in Hawaiian rain forests, comparing their functionality to that of native forest surveys along a natural gradient of increasing nitrogen availability. Hawaii is illustrative of regional patterns in species change, with much higher regional plant richness in recent years. At local scales, novel forests had significantly higher tree species richness and diversity of dominant tree species than native forests did, but aboveground biomass, productivity, nutrient turnover, and belowground carbon storage were not significantly different between novel and native forests.

These examples of novel ecosystems are either part of the productive landscape or have developed after the abandonment of productive activities, and exotic species have become part of the floristic composition. They are self-maintained functional ecosystems, delivering environmental services such as sheltering the local biodiversity. Restoration would imply vast and costly efforts that probably should not be targeted for restoration activities.

Species used for restoration

A main concern in restoration should be the set of species to be used. Patterns of early succession to forest after the land has been abandoned also depend on the species of trees introduced (Rey Benayas *et al*. 2008) and many techniques have been employed which include numerous species: enrichment plantings, scattered tree plantings, dense multi-species plantings, mixed species plantations, agroforestry, among others. Moreover, Mascaro *et al.* (2012), based on their work in Hawaii, concluded that fundamental ecosystem processes will endure even after impressive losses of native species diversity if basic functional roles are offered by introduced species.

Species selection for restoration plantations. Many restoration efforts require tree sowing, planting, or transplantation. The choice of species can shape the rate and trajectory of restoration processes and define their success. The timing of arrival (or introduction of species) is essential. In a review, Weidlich *et al.* (2021) report that minor delays in arrival time, as opposed to coincident arrival of species in temperate grasslands, can encourage differences in successive community composition and ecosystem functions. This point should be taken into account when working in other ecosystems.

Experimental data on the responses of native species to propagation and restoration treatments throughout a range of local conditions are required (Lu *et al.* 2017). Núñez-Cruz *et al.* (2018) studied reproductive seed germination and phenology of eight species collected in the tropical dry forest. Also, inappropriate species that have no use or are of no interest to the local inhabitants where the restoration is taking place can lead to unsuccessful restoration (Sayer 2005). Therefore, the species selected should be of broad ecological importance, have traditional economic or another type of value to local inhabitants, or have value in existing or potential markets. There are gaps in our knowledge on the phenological patterns of native species. This causes a small selection of options of native plants and a lack of efficient collecting protocols (Luna-Nieves *et al.* 2017). The authors analyzed the reproductive phenology of 14 native tree species collected from dry tropical forests used in reforestation and restoration projects. Based on their results they made recommendations for optimal collecting seeds schedules. Knowledge on fruiting patterns, seed viability, and germination are useful for adequate decision-making for seed collection and plant propagation of the study species to be used in restoration activities (Núñez-Cruz *et al*. 2018), which can increase success and lower restoration costs.

Very few restoration projects identify sets of plants or evaluate the traits that augment particular functions such as resistance to invasion by exotic species (Funk *et al.* 2008), primary productivity (Jiang *et al*. 2019), seed dispersal (Camargo *et al.* 2020), or pollination services (Ceccon & Varassin 2014). M'Gonigle *et al.* (2016) developed a computational tool that helps identify a plant mix that optimizes criteria such as pollinator visitation, richness, and phenology. They tested the tool in mixed native vegetation, vegetable farms, and orchards in Northern California's Central Valley. A crucial first step is understanding which species combination to reintroduce to restore ecosystem services and maintain a stable restored community and using trait-based models to produce arrays of species abundances to test theories that are useful for achieving functional results (Laughlin *et al.* 2018). Carlucci *et al.* (2020) systematically reviewed the literature to evaluate how ecosystem services are linked to functional traits across organisms, different types of ecosystems, and continents. They state that flexibility when selecting alternative sets of functionally comparable species can enable broad-scale functional restoration, mainly in the tropics. Choosing species to accomplish target services is anything but trivial because different species may support a variety of ecosystem services (Díaz *et al.* 2007).

Multi-purpose trees may have an especially important role in local communities. The local inhabitants often have extensive traditional knowledge of propagation methods, species suitability for specific light and soil conditions in their areas, and management methods for a range of tree species, all of which can help in designing effective restoration projects (Tolentino Jr 2008). It is of crucial importance to include the social and cultural values that people attach to forest plant and animal species in the criteria used for species grouping and selection (Uprety *et al.* 2012).

Méndez-Toribio *et al.* (2021) mention that the reasons plants are selected for restoration projects in Mexico often have little relation to restoration objectives, which are even disregarded by practitioners. Accessibility and readiness in nurseries, or sought-after traits frequently determine which species are used rather than their function in a specific ecological process or ecosystem function (Stanturf *et al.* 2014). In general, there is insufficient information on the traits of tropical plants, and even if there are published papers with information, local nurseries do not have many options of useful plants for agroforestry, silvopastoral, and restoration (Luna-Nieves *et al*. 2019).

Society and its link to restoration

Ecological restoration is inseparable from society. Goals for social and human well-being, including those that recover or reinforce ecosystem services, must be acknowledged together with ecological targets when planning a restoration project (Gann *et al.* 2019). This implies working with people, working with communities. Thus, success in restoration projects should include well-defined expectations but also a clear understanding of the specific social context (Stanturf *et al.* 2014). Acknowledging stakeholders' expectations and interests, and their direct involvement are key to ensuring that both nature and society mutually benefit. The social aspects of restoration are rarely explored and local rural communities seldom participate (Wehi & Lord 2017, Reyes-García *et al.* 2019, Ceccon *et al.* 2020, van Noordwijk *et al*. 2020, Martínez-Garza *et al*. 2022). Involving these stakeholders transforms them into the authors (*sensu* Pesci *et al.* 2007) of a restoration project and not only enhances their participation and involvement but ensures their allegiance to the project and increases the possibility of success and long-term commitment. Effective social participation acquired through a dialogue among participating stakeholders can expand social capital and modify relationships and interactions with the natural environment (Ceccon *et al.* 2020). This participatory process can also boost a more substantial political and social transformation, which may concede rural inhabitants to become an integral part of the larger social and political systems prevailing and thus advance the governance process (Ceccon *et al.* 2020). Involvement is not a one-way action; it has to be both ways, implying responsibilities from the community but also from the practitioners and/or scientists towards the local people.

Sustainability, traditional and local ecological knowledge. Achieving environmental sustainability is one of the biggest challenges facing humanity. Cebrián-Piqueras *et al.* (2020) say that a fundamental value of sustainability science is understanding that the insertion of local ecological knowledge (LEK), perceptions of ecosystem service provision and landscape vulnerability enhance sustainability and resilience of socio-ecological systems. LEK is defined as local, place-based knowledge of the land and its processes. Its application leads to fertile lands and maintains ecosystems in good health, augmenting biodiversity and improving ecosystem resilience (Gann *et al.* 2019). Sound ecological restoration uses many types of knowledge. In this sense, both local and traditional ecological knowledge (TEK) are indispensable for ecological restoration, in addition to practitioner experience and scientific discovery (Gann *et al*. 2019).

Uprety *et al*. (2012) and Reyes-García *et al*. (2019) state that the contribution of TEK to the conservation, management, and sustainable use of natural resources is increasingly recognized and respected as a source of information. There is a greater understanding that successful ecological restoration depends on the smooth coordination of science and TEK, even though the latter is rarely included in restoration programs (Uprety *et al.* 2012, Méndez-Toribio *et al*. 2021). There is still considerable debate about this. Some studies indicate that local and TEK offer strong groundwork for ecological restoration (Higgs 2005), while others doubt their scientific validity and question their usefulness at the local level only, while still others are troubled about the ethics of TEK being misused for academic and policy purposes (Chalmers & Fabricius 2007). Lam *et al*. (2020) reviewed the literature to see how indigenous and local knowledge was characterized in peer-reviewed empirical scientific papers on conditions of transformation, transition, and change. Their results indicate that indigenous and local understanding of transformation is actually ignored in the scholarly discourse of transformation. Various authors go farther and are much more emphatic in their defense of Indigenous Peoples' rights, which implies protecting TEK, and the restoration of knowledge, language, biodiversity, and ecological functions (Robinson *et al.* 2021). Elias *et al*. (2021) said there should be a turn toward people-centered restoration strategies, and list 10 people-centered rules to guarantee restoration projects are acceptable. Restoration projects have to go accordingly to established international agreements and partake in proactively safeguarding intellectual property and data sovereignty rights. Thus, in many academic institutions the interaction between researchers and people is still a pending ethical discussion.

Social participation has been recognized as fundamental to the success and sustainability of forest management projects (Bray and Merino-López 2002) but is not usually included in restoration project planning. Local communities mainly participate in activities such as field labor (Ceccon *et al.* 2020, personal observation). Rarely do scientists and local inhabitants work together to co-design restoration projects.

Uprety *et al.* (2012) give several examples of the use of TEK in ecological restoration and planning in different countries (Canada, China, New Zealand); other examples include the restoration of fallow forests after swidden cultivation in Mexico, Thailand, and India. TEK has also been applied to select pioneer tree species that have economic and ecological value in restoration and provides knowledge of natural regeneration processes in rotational shifting cultivation applicable to forest restoration (Ramakrishnan 2007, Diemont & Martin 2009).

Restoration in Mexico, land ownership and environmental services. Land use changes and development are complex from both sociological and environmental perspectives. Latin America has the planet's greatest land reserves for agriculture and the fastest rate of agricultural expansion during the 21st century (Graesser *et al*. 2015) with 57 % of new pastureland and 17 % of new cropland replacing its forests. Bonilla-Moheno & Aide (2020) analyzed land use between 2001 and 2014 in all of Mexico's ecoregions. Land use patterns have changed notably in the 40 major ecoregions, but in general, woody vegetation and cropland cover increased while pasture cover declined. In a worldwide analysis, Rey Benayas *et al*. (2007) specified three major drivers of agricultural land abandonment: ecological drivers, socio-economic drivers, and maladapted agricultural systems and land mismanagement.

There is a worldwide trend toward urbanization, leading to land abandonment in rural areas and an increase in areas with no cultivation, which might become a benefit for humans, such as unassisted or natural revegetation and reforestation, water regulation, soil recovery, improved nutrient cycling and increased biodiversity and wilderness (Rey Benayas *et al*. 2007). Over time, we will probably see a surge in the unassisted revegetation and reforestation of many abandoned rural areas. This offers an important opportunity for restoration ecologists and practitioners to make sure that the result is successful. Since the land still has owners, they should participate in these restoration efforts.

High biodiversity is strongly linked to cultural diversity, especially in a multicultural country. As Frainer *et al.* (2020) mention in their recent paper entitled "Cultural and linguistic diversities are underappreciated pillars of biodiversity", they are all strongly linked. These conditions present tough challenges to restoration efforts (Lindig-Cisneros 2010) because this implies very diverse perceptions of nature, diverse cultural land management practices, some of them not fully understood, and extensive use of many local resources, among others. In many cases, restoration projects need to establish a dialogue among cultures that usually share little in terms of their perceptions of Nature. The socioecological complexity of restoration in Mexico (and in many other countries in Latin America) is linked to private or collective land ownership -only 8 % of the land belongs to the state (Lindig-Cisneros 2010). Restoration efforts involve working with and coming to agreements with the landowners who rely directly on the land for subsistence, and this adds another layer of complexity to restoration (Lindig-Cisneros 2010). During the last decade, 80 % of the forests in Mexico belonged to local communities or *ejidos* (Ceccon et al. 2015). This makes indigenous communities one of the crucial decision-making groups in the country with respect to ecosystem management. Their collaboration is essential because it is on their land where the ecosystems that provide essential environmental services to all of us are found.

The situation in Mexico was analyzed by López-Barrera *et al*. (2017) in a review of 206 articles (1995-2016). Studies of forest ecosystems accounted for 71 %, and mainly addressed the recovery of tree and shrub species. One of their conclusions is the need for a national scientific restoration policy. The objectives and goals of restoration projects were evaluated by Méndez-Toribio *et al.* (2018), revealing that 53 % set the goal of recovering the habitat and its connectivity for endangered species. In 81 % of the projects, the recovery of the plant species was sought, with bird recovery in second place (43 %). Martínez-Garza *et al.* (2021) analyzed the planning phase of restoration projects and found that the baseline was assessed mainly with biotic than with abiotic variables; and social variables were seldom evaluated. Méndez-Toribio *et al*. (2021) conducted a countrywide assessment analyzing the results of restoration projects. They evaluated the technical aspects of the interventions, ecological and socio-economic outcomes and monitoring (see Table S1).

Restoration aimed to restore, to conserve, to produce

Currently, natural regeneration restores more forest cover (45,000 km^2) in regions that have been deforested than tree plantations (28,000 km^2) do, and possibly at a lower cost than actively planting forests (FAO 2006).

Two contrasting restoration approaches have been used to recover forests and woodlands: (1) unassisted forest regeneration (*sensu* Chazdon & Guariguata 2016) through natural colonization by shrubs and trees that enhance seed sources and accelerate secondary succession and connectivity, and (2) restoration through the establishment of trees, with higher costs, requiring diverse management techniques intended to create a forest with a specific composition or structure (Rey Benayas *et al*. 2008).

Both approaches face distinct challenges. Their success depends on local and regional conditions. Many tropical and humid temperate ecosystems can recover quickly with little or no intervention when the soil has not been severely degraded by former land use and there is connectivity or proximity to nearby forests for seed dispersal. This contrasts with the very slow regeneration that occurs in environments with low primary productivity (Rey Benayas *et al*. 2008). Zahawi *et al*. (2014) mention other costs associated with unassisted restoration: longer recovery time, the plot may be seen as abandoned land, which can have legal consequences, and economic costs (putting up and repairing fences, site surveillance). The restoration literature shows an impressive number of papers reporting the results of experiments and observations. Nevertheless, we need permanent areas under observation and experimentation for more years than a researcher devotes to a research theme, where there is a memory of the initial conditions, subsequent management actions, and integral evaluations. Their size should allow evaluation of environmental services, presence of food chains, possibilities to analyze the impact of fire or floods, etc. They should form part of academic field stations, biosphere reserves and federal land. When we convince local stakeholders to restore their land, we should have enough information to ensure it will fulfill their expectations and ours.

Poorter *et al.* (2021) analyzed how12 forest attributes recovered during succession using 77 sites in the tropics. They found that after 20 years, forest attributes attain 78 % of their old-growth values. Secondary forests recover remarkably fast in species richness but slowly in species composition; secondary forests take a median time of five decades to recover the species richness of old-growth forests (80 % recovery after 20 years) (Rozendaal *et al.* 2019). They conclude that tropical forests are highly resilient to low-intensity land use and that secondary forests should be embraced as a low-cost, natural solution for ecosystem restoration, biodiversity conservation, and climate change mitigation (Poorter *et al.* 2021). Thus, there are several restoration techniques that have shown to promote the establishment of secondary forests. The following sections show some of the results obtained. They can be easily set up with local communities as many understand the importance of standing trees, living patches of remnant forests, and living fences. Older farmers still remember the swidden cultivation that their fathers used. Also, many of these techniques are naturally taking place and can be part of more extensive restoration projects and help the tropical world restore their landscapes through promoting secondary forests.

Agroforestry and silvopasture. Holl & Howarth (2000) state that the main obstacles to most restoration projects are cost and competing land uses. This is why so much research has focused on agroforestry and silvopasture, which include multiple land uses and a variety of trees in an attempt to balance current human needs and the conservation of ecosystem services (Grainger 1993). With the growing demand to restore abandoned agricultural and cattle ranching lands in the tropics, it is essential to explore different models, techniques and management practices for restoring these lands. Measures taken should be appealing to rural people, cost-effective, offer income, and encourage natural forest recovery.

The restoration of traditional agroforestry systems is advancing; it is now seen as a long-term solution to the global socioecological crisis, mainly in poor rural regions (Aguirre-Salcedo & Ceccon 2020). Mayan ecosystem management and TEK represent a sustainable alternative for conservation and restoration in Mesoamerica. At least five Mayan groups living in Mexico and Central America, use TEK for conservation of their territories, production for local consumption, and restoration of the tropical forest from early succession patches to late succession, using an agroforestry system and swidden cultivation. Over 33 species are actively used for restoring ecosystems. These agroecosystems provide service to the ecosystem and at the same time, service to humans in terms of numerous products obtained at all stages of succession (Diemont *et al.* 2011). Vieira *et al*. (2009) propose that agro-successional restoration, defined as incorporating a series of agroecology and agroforestry techniques applied during a transition period at the beginning of forest restoration, can be easily and extensively applied to overcome socioeconomic and ecological difficulties in the recovery of agricultural land.

Extensive cattle ranching is the number one reason for deforestation in almost every Amazon country; it is responsible for 80 % of current deforestation (Nepstad *et al.* 2008). Cattle was introduced by the Spaniards almost as soon as they arrived in the Americas. There has not been much research on what cattle mean to local rural inhabitants in the American continent from the cultural point of view (Guevara Sada & Moreno-Casasola 2008). A few head provide milk, products to sell, and can always be sold when the family needs cash (sickness, celebrations, etc.). For many rural inhabitants, the economic value of cattle is crucial. And this practice has also become part of the local culture in many regions (*e.g.*, Maldonado *et al.* 2013, among others). When asked, many farmers respond they are ranchers and not farmers, even if they own just a few cows (personal observation). In Mexico, Argentina, the southern USA, and probably many other countries there is a dress code that distinguishes ranchers from farmers, which can be quite expensive and is a matter of personal pride, allowing those with the same activities and interests to identify each other. I believe this indicates that cattle ranching is socially important and will be part of our lives for a long time, and that any transition towards a more forested landscape will be slow.

Silvopasture is the deliberate mixing of trees and grazing cattle activities on the same land. They are intensively managed for both forest products and leaf forage; thus, they provide short- and long-term incomes for families. In this sense, silvopastures are a promising way of changing attitudes and incorporating trees, the first step in any soil and forest restoration project.

Restoration based on the acceleration of secondary succession. Florentine & Westbrooke (2004) listed the main obstacles to natural regeneration on abandoned and degraded pasturelands: weed infestation, lack of an indigenous soil seed bank, scarcity of seed supply/movement, soil compaction, exhaustion of soil nutrients, and unfavorable microclimate and microhabitat. Many unassisted restoration processes and low-cost restoration methods concentrate on nucleation processes that facilitate seed arrival and seedling establishment (Guevara & Laborde1992, Corbin *et al.* 2016) and help accelerate secondary succession. In the natural nucleation process, the primary colonizing plants establish in patches and spread outward clonally and/or facilitate the colonization of other species. In this sense, these nuclei represent an alternative for restoration by giving priority to the natural processes of succession taking place in nature (Reis *et al*. 2010). There are several nucleation techniques (standing trees, living fences, windbreaks, perches, woodland patches, wooded islets, which provide shelter for animals, planting herbaceous shrubs, transplanting soil and seed banks, forming ecological stepping-stones with functional groups; Reis *et al*. 2010). These all promote landscape connectivity; that is, inward flow (receiver connectivity) and outward flow (donor connectivity) (Reis *et al*. 2010). They also add structural and floristic complexity to both the agricultural and pastoral landscapes while enhancing landscape connectivity and are a means of conserving biodiversity (Guevara *et al*. 1998; Harvey *et al*. 2004).

Standing trees.- Isolated trees are conspicuous features on many fragmented tropical landscapes in Mexico (Figure 3), Central and South America, some regions of Africa, and Australia (Guevara *et al*. 1998, Harvey *et al*. 2004). The practice of leaving trees standing in the field is part of the traditional management of these ecosystems carried out by various ethnic groups and seems to be linked to slash and burn agriculture (Guevara & Laborde 1992, Carrière 2000). These trees are currently linked to small-scale livestock farming by peasants who preserve agricultural traditions, with some trees being spared when the forest is cut down to make way for an agricultural field, which they will later turn into a pasture.

Research indicates that remnant pasture trees play a critical role in natural forest recovery by increasing seed dispersal, ameliorating the microclimate, and increasing soil nutrients (Guevara & Laborde 1993, Guevara *et al.* 1998, Rhoades *et al.* 1998, Otero-Arnaiz *et al.* 1999, Duncan & Chapman 1999). Many species are left standing, but *Ficus* trees are extremely important components in tropical ecosystems, as they produce large, nutritionally rewarding fruit crops and attract seed dispersers (Cottee-Jones *et al*. 2016), and they may be more effective forest restoration agents than other remnant trees in disturbed landscapes. A striking variety of birds and bats are attracted to the voluminous tree crowns of these solitary trees: 47 species of visiting frugivorous birds (Guevara & Laborde 1993), representing almost one third of the total frugivorous avifauna, were reported for the Reserve of the Los Tuxtlas Biological Sta-

Figure 3. Currently pastured landscapes in Los Tuxtlas, Veracruz, Mexico, include a large number of tall standing trees, some very tall with smaller crowns (A) and others with very extensive crowns like the fig trees (B) that form isolated fragments of tropical forest that act as nuclei for secondary growth, along with corridors of riparian vegetation, living fences and solitary standing trees, with two to six trees per hectare (C).

tion (Universidad Nacional Autónoma de México), along with 652 bats belonging to 20 species (56 % of the species reported for the area; Galindo-González *et al*. 2000). The floristic list for these pastures includes 343 species, 138 of which are trees (Lira-Noriega *et al*. 2007). One hundred and seventy of these species are endozoochorous, *i.e.*, dispersed by birds and fruit bats. Zwiener *et al*. (2014) in Brazil recorded seed and seedling abundance, species richness and composition under isolated trees, bird perches and in open pasture. Their results suggest that isolated trees enhance forest re-establishment, and artificial bird perches offer a complementary way of restoring tree abundance in abandoned pastures.

Ant species richness, ant abundance and beetle abundance per trap were higher near isolated trees than in the open fields. Ant species richness was positively correlated with tree size (Dunn 2000). The protection and restoration of isolated trees and small clumps of woodland in cleared landscapes also contribute to mammal conservation as seen in gap-crossing by gliding marsupials (van der Ree *et al.* 2003).

The main barriers to forest regeneration in pastures are the absence of forest seeds and conditions hostile to the germination and establishment of forest species (Nepstad *et al*. 1990). The results obtained in Los Tuxtlas illustrate how isolated trees favorably change these conditions since they attract frugivorous vertebrates that disperse the seeds of forest species into the pasture (Guevara & Laborde 1993, Galindo-González *et al*. 2000). Under their shade they create a microclimate and edaphic conditions favorable to the establishment of rainforest plants (Popma & Bongers 1991, Williams-Linera *et al*. 1998), and reduce competition with heliophytic species, as long as livestock are excluded (Figure 4).

Artificial perches.- Artificial structures have been tested in the restoration of both temperate and tropical forests (Figure 4). These structures appear to have potential for use in open areas in regions with tropical forests where the seeds of 50-90 % of the canopy trees and nearly 100 % of shrubs and sub-canopy trees have adaptations for animal dispersal (Howe 1984). Increased vertical structure may serve to attract birds farther into the pasture, thus boosting seed dispersal (Holl 2002). The results of a meta-analysis examining the effect of artificial perches and control sites without perches indicated their use enhances the abundance and richness of seeds that arrive in altered areas from neighboring native ecosystems (Guidetti *et al*. 2016). Similar results were obtained in tropical forests (Holl 2002, Tomazi & Castellani 2016, Iguatemy *et al*. 2020), in an abandoned pasture on sand dune soils in Mexico (Guevara Sada *et al*. 2016), and in Mediterranean old fields (La Mantia *et al*. 2019).

Some authors do not think bird perching structures alone are an effective strategy, because while they serve to enhance seed dispersal, they do not reduce grass cover (Holl *et al*. 2000). A small number of studies have evaluated seedling establishment under the perches when pasture grasses were cleared (Ferguson 1995), though Guidetti *et al*. (2016) found seedling density was higher in open areas with artificial perches than in control sites without perches. Combining the use of perches with methods that help reduce pasture grasses, such as clipping or herbicide application, can facilitate recovery (Ferguson 1995, Elgar *et al*. 2014).

Tree stakes.- Planting vegetative stakes to create tree islands in pastures accelerates forest recovery by overcoming several impediments —seed dispersal and harsh microclimatic extremes— and presents a simple, broadly applicable alternative for facilitating forest regeneration in abandoned pastures. “Tree islands” created with three stake sizes (64, 16, and 4 m^2) of two native species were fashioned to serve as ‘‘recruitment foci’’. Seed-dispersing birds showed an overwhelming preference for islands; frugivores visited large islands more often and for longer periods than small islands. Seedlings were established under these islands (Zahawi & Augspurger 2006). Oversized stakes may be planted as solitary individuals in restoration sites to mimic the role of remnant trees in forest recovery, as shown by Zahawi (2008) using 4 m-tall stakes of *Ficus pertura, Bursera simaruba*, and *Erythrina poeppigiana*. Thus, planting vegetative stakes to fashion tree islands in abandoned pastures hastens forest recovery and represents a simple, applicable choice for facilitating forest regeneration.

Woodland islets.- A number of researchers have documented another approach to nucleation in tropical pastures (Kolb 1994, Vieira *et al.* 1994, Holl *et al.* 2000). They observed how small patches of trees and shrubs rapidly spread in abandoned pastures (Figure 4). Therefore, the practice of planting patches may produce a certain spatial diversity, characteristic of the ecosystem. Woodland islets have been successful under specific conditions, *i.e.*, sites with low primary productivity as in Mediterranean areas or with a long history of land clearance. Under these conditions, species diversity will be low with some functional groups absent unless there is some management. Thus, planting many small, dense blocks of native trees enhances biodiversity and provides a range of ecosystem services (Rey Benayas *et al.* 2008). The establishment of recruited seedlings was ten times higher under the cover of planted trees than in grassy controls in southern Mexico (de la Peña-Domene *et al*. 2014). After 76 months of cattle exclusion, 94 % of the newly recruited shrubs and trees in experimental plots belonged to species that the authors had not planted.

Restoration of fallow lands.- Currently, the tropical forest landscape in southern Mexico and northern Central America (Mesoamerica) has great biodiversity and a high level of resilience, as corroborated by its potential for natural regeneration. This region has been inhabited for more than 3,000 years, during which people designed their landscape, applying some of the main ecological processes of the ecosystem (Guevara 2016). During slash and burn agriculture (shifting cultivation, swidden, also known in Spanish as *roza, tumba y quema*), the *acahual* (secondary vegetation) develops during the fallow period or resting phase. This agricultural system replicates the process that follows when the canopy of the forest is opened by natural treefall. The success of the traditional swidden cultivation was due to the gentle domestication of a regeneration process that conserved the water, the fertility cycles of the soil, and the availability of habitats for plant and animal species. People designed the landscape, respecting the ecological processes of the ecosystem, favoring the movement of plant and animal species through the landscape (connectivity), thus managing the natural regeneration of the forest (Guevara 2016). An example is the planting and care of several tropical forest tree species during the fallow period of the multi-successional swidden system of the Lacandon people (Chiapas, Mexico) to facilitate the restoration of soil fertility, a process during which the nitrogen and soil organic matter content increase (Falkowski *et al.* 2016).

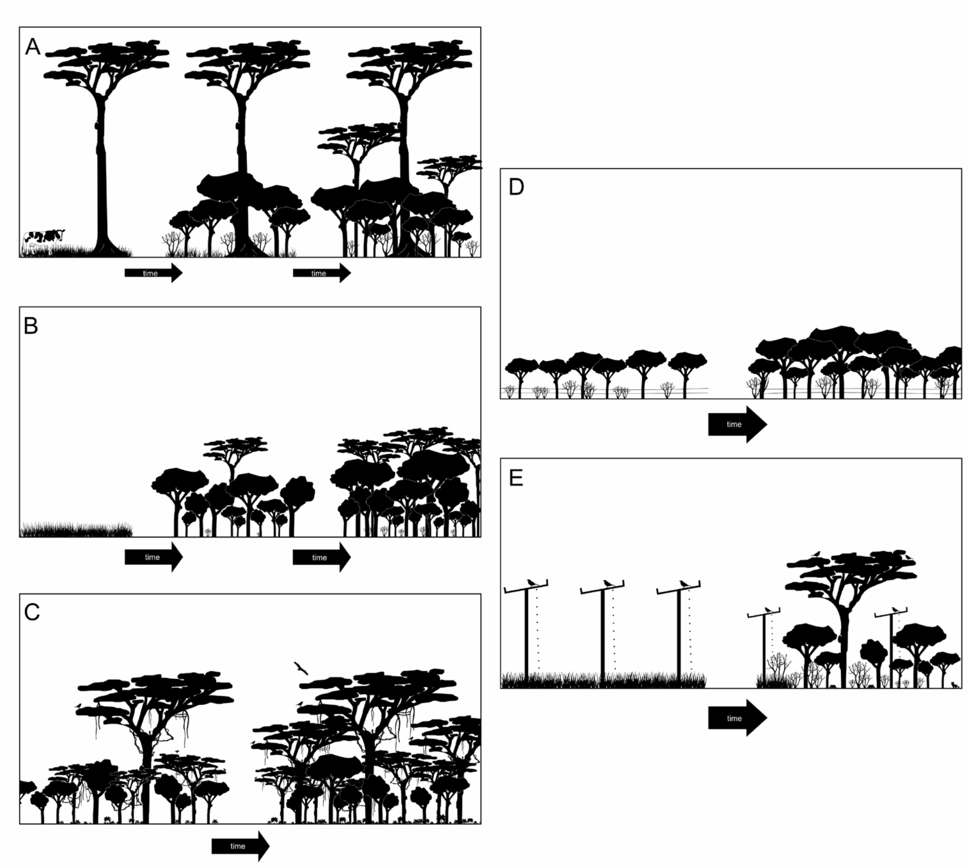

Figure 4. Model showing structural changes in different nucleation techniques over time. (A) standing trees, (B) woodland islets, (C) patch of tropical forest, (D) living fences, (E) artificial perches. The width of the arrow indicates the time required to naturally increase species composition and to achieve a more complex structure.

Fire as a restoration tool.- Fire is a natural part of the ecology of many forest ecosystems. Indigenous people with traditional practices and other local landowners worldwide use fire for territorial management and cultural expression, with the result of promoting resource availability, diversity, and resilience (Welch & Coimbra 2021). Indigenous peoples' lands and traditional burning practices are regularly associated with landscape conservation, the preservation of vegetation cover, and biodiversity (Charnley *et al.* 2007, Miller & Davidson-Hunt 2010). Recent research with the Xavante people (Brazil) has shown that hunting with fire helps maintain and recover cerrado vegetation cover (Welch & Coimbra 2021). The Pimentel Barbosa reserve exhibits evidence of reforestation in combination with periodic hunting with fire. Research indicates that this type of effective fire control should begin with territorial sovereignty and incorporate Indigenous and traditional communities as equal conservation partners (Welch & Coimbra 2021).

Log piles.- Finally, it is worth mentioning the new approaches arising from management practices. The piles of branches and logs left after felling a forest to open up agricultural areas help reduce the light level and temperature at the soil's surface, in addition to providing safe sites for woody seedling establishment (Holl *et al*. 2000, Peterson & Haines 2001). They also serve as perching sites and shelter for a number of smaller bird species. In Venezuela, Uhl *et al.* (1982) built artificial piles of logs, which resulted in higher woody seedling establishment the first year after pasture abandonment. Seed-dispersing birds are attracted to piles of woody debris that are built as erosion barriers, which become seed dispersal foci (Rost *et al.* 2012). In abandoned mining structures in southeastern Spain where there is climate and edaphic stress, Oreja *et al.* (2020) found pine log piles significantly improved microclimate conditions and accelerated plant establishment in unfertile, metal-contaminated soils.

In summary, the people of Mexico and Central America, Indonesia, and other countries have accumulated considerable experience and a vast pool of TEK that has proven to be both productive and capable of maintaining ecological integrity. Nowadays, their knowledge can offer a practical approach to tropical forest restoration because it embraces the selection of useful plant species that encourage the early successional stages of the restoration process (Ramakrishnan 2007, Diemont *et al.* 2006, Uprety *et al.* 2012), conservation of their lands, production for local consumption, meeting family needs (Diemont & Martin 2009), and restoration of early succession patches to late succession patches. It also restores soil fertility and regenerates secondary forests in three successional stages of fallow, recognized as a 5–10 year stage with shrubs, a 10–25 year stage called *acahual*, and the 25+ stage called *selva alta*, a mature forest which is structurally indistinguishable from the primary forest, although residents consider it as non-primary (Diemont & Martin 2009, Diemont *et al.* 2011, Uprety *et al.* 2012).

Closing comments

Restoration is a long-term social and ecological process. There are many things yet to be done, investigated and resolved. To list just a few:

(1) We need permanent restoration plots in academic field stations, biosphere reserves and on federal land, where experimentation can take place over many years. This should involve community participation. Budgets over several years need to be allocated, which means transforming current research and funding policies.

(2) Local communities should participate in and co-design restoration projects as active authors throughout the process.

(3) Research on restoration, the species and ecological processes, making use of TEK alongside different indigenous groups should be emphasized, supported and reinforced. If we can manage species at different stages of restoration, with the active participation of local communities, a combination of both low-cost unassisted restoration and restoration techniques can be used. Restoration should truly become a nature-based solution for recovering biodiversity and ecological functions. An experimental approach using different sets of species will open new possibilities for scientific research and help us gain a better understanding of the required course of action.

(4) In countries where there is a still a strong dependence on land to meet everyday needs, the transition from productive agricultural and pastoral land to woodland will be slow culturally and economically, but it also represents one of the most promising approaches. Restoration practices that enhance the recovery of productivity, connectivity, and food and water security should be encouraged.

(5) There needs to be work with the federal, state, and local governments to increase the perception of restoration needs. Their active participation in these programs is of the utmost importance.

Acknowledgments

We thank Graciela Sánchez for her help carrying with the web search, Roberto Monroy and Kerenha Hernández for the figures, and Bianca Delfosse for help with the English version of the manuscript. Thank you to the two anonymous reviewers who helped clarify and have a better contribution.

Supplementary material

Supplemental data for this article can be accessed here: https://doi.org/10.17129/botsci.3149

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Guest Editors: Jorge A. Meave, Ken Oyama, Victoria Sosa, Arturo de Nova.

Author contributions: PMC is the only author responsible for the ideas and writing the manuscript.