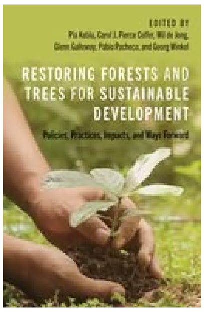

Restoring Forests and Trees for Sustainable Development: Policies, Practices, Impacts, and Ways Forward

Pia Katila (ed.) et al.

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7

Forest restoration, biodiversity, and ecosystem services

Rens Brouwer, Frans Bongers, Marielos Peña-Claros, Pieter A. Zuidema, Pedro Brancalion, Madelon Lohbeck, Alejandra Hernández Guzmán, Alan Heinze, Joannès Guillemot, Koen Kramer, and Douglas Sheil

7.1 Introduction

7.1.1 Ecosystem services from forest restoration

Functioning ecosystems support life on earth. Between 2001 and 2005, over a thousand experts from various disciplines assessed the consequences of ecosystem change for human well-being, resulting in the Millennium Ecosystem Assessment (MEA 2005). These authors concluded that approximately 60% of ecosystem services (ES) are being degraded. Forests are among the most important ecosystems providing ES: they sustain millions of species, the air we breathe, and the fresh water we drink, among other things vital to livelihoods. Since 1990, global forest cover has been reduced by 420 million hectares; over half of the remaining forest is degraded (FAO and UNEP 2020). Forest restoration can play an important role in regaining and improving ES and thus contribute to human well-being. Many of the United Nations (UN) Sustainable Development Goals (SDGs) may be realized, in part, through forest restoration (Melo et al. 2021). Forest restoration goes beyond tree cover and can contribute to and sustain various ES (Figure 7.1). There is much research on the effects of forest restoration on ES, and this chapter aims to review the results of these studies.

7.1.2 Ecosystem services frameworks

ES are classified in various ways using different criteria. The Ecosystem Services MEA framework (MEA 2005) provided the basis from which the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin 2018). More recently, the Nature's Contributions to People (NCP) framework (e.g., Díaz et al. 2018) was derived by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). We use the widely recognized CICES framework to review current findings of forest restoration effects on ES. CICES classifies ES as provisioning, regulating, maintaining, and cultural (Figure 7.1).

Rens Brouwer, Frans Bongers, Marielos Peña-Claros, Pieter A. Zuidema, Pedro Brancalion, Madelon Lohbeck, Alejandra Hernández Guzmán, Alan Heinze, Joannès Guillemot, Koen Kramer, and Douglas Sheil, *Forest restoration, biodiversity, and ecosystem services* In: *Restoring Forests and Trees for Sustainable Development.* Edited by: Pia Katila, Carol J. Pierce Colfer, Wil de Jong, Glenn Galloway, Pablo Pacheco, and Georg Winkel, Oxford University Press. © Oxford University Press 2024.
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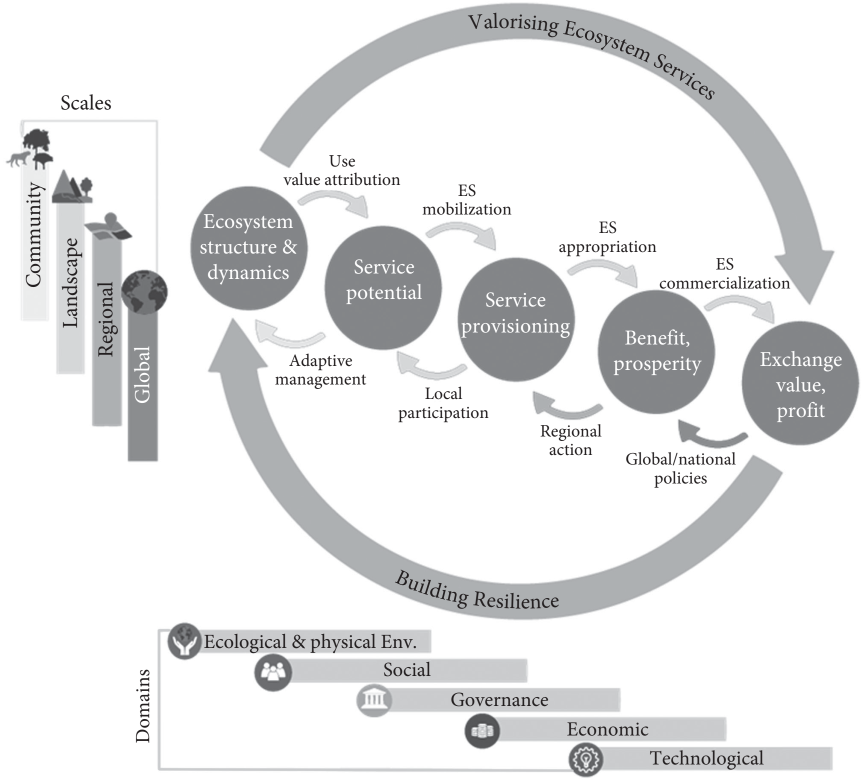

Figure 7.1 Illustration of the forest ecosystem service supply cascade. Figure is adapted from Haines-Young and Potschin (2011) and Kramer et al. (2021). (ES = Ecosystem Service.) The arrows going from left to right above the green circles represent the cascade or flow of ES from a forest ecosystem to societal domains; while the arrows from right to left indicate the transfer of stakeholder impacts and societal domains on the functioning and resilience of forest ecosystems. Horizontal and vertical bars illustrate the domains and spatial scales at which services and benefits are relevant.

These frameworks help identify specific services that can be targeted for restoration, which helps planning restoration for multiple benefits (Alexander et al. 2016). In this chapter we will address biodiversity, nutrient cycling, water cycling, provisioning and cultural services. Climate action and carbon dynamics is covered in Chapter 6.

7.1.3 Scope and methods

Reviewed journal articles on forest ES from 1994 to 2017 (Acharya et al. 2019). While findings show that ES is receiving increased attention, coverage in much of the tropics remains limited. An area of growing interest concerns augmenting and sustaining ES through forest restoration. As emphasized in the International Principles

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and Standards for the Practice of Ecological Restoration, forest restoration aims at recovering all or part of forest ecosystem characteristics (Gann et al. 2019). These characteristics range in scale from individual plant–soil interactions at the micro-level to community–environment interactions at the macro-level (Figure 7.1). Forest restoration provides an opportunity to alter these characteristics to address specific needs, through species selection and management (Figure 7.2). Forest restoration has a variety of approaches, and the approach depends on conditions, context, and goals (Figure 7.2). Some of these factors have been widely assessed; for example, a meta-analysis of 247 studies including 196 landscapes shows that restoration success is more likely when habitats are less fragmented (Crouzeilles and Curran 2016). While the distinction between active and passive restoration approaches has often been emphasized, this dichotomy is increasingly being replaced by a continuum of options (Chazdon et al. 2021).

This chapter summarizes current knowledge linking forest restoration with ecosystem characteristics. We examine a selection of ecosystem characteristics—properties, processes, functions, and services—linking forest restoration to environmental changes. We selected the following themes: biodiversity, water cycling, nutrient cycling, provisioning services, and cultural services. First, we describe the general role of biodiversity. Biodiversity is also considered throughout the chapter because of its interwoven relationship with ES recovery. Second, we review how forest restoration affects the four ES (Figure 7.1 and Infographic 7.1). Each of the four

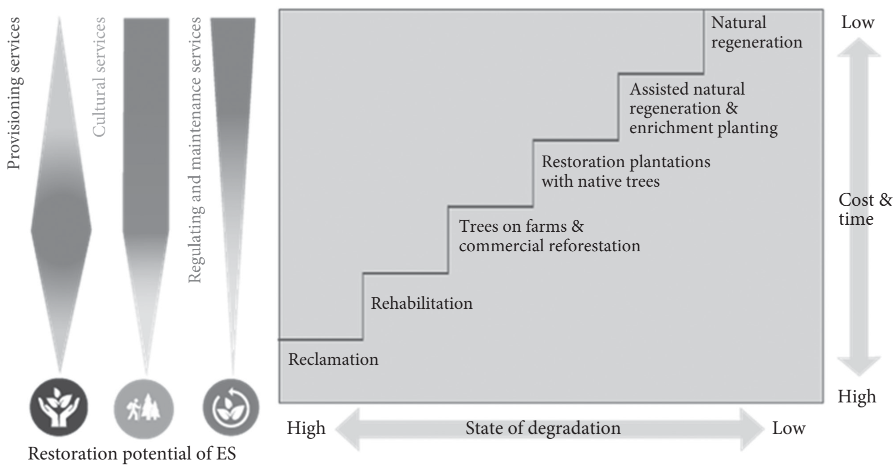

Figure 7.2 The restoration staircase. Depending on the state of degradation of an initially forested ecosystem, a range of management approaches can at least partially restore levels of biodiversity and ES given adequate time and financial investment (capital, infrastructure, and labor). Recovery potential of biodiversity and particular ES depends on the restoration method. See the infographic at the end of the chapter for a more detailed overview. Source: staircase adapted from Chazdon, R. L. 2008. "Beyond deforestation: Restoring forests and ecosystem services on degraded lands." Science 320 (5882): pp. 1458–1460. Reprinted with permission from AAAS.

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ES topics is supported by a table which shows the general relationship between forest restoration and the ecosystem characteristics (in these tables, forest restoration is generalized as an increase in tree cover or tree diversity). Third, we discuss trade-offs between ES for different restoration methods and their applications in specific land uses. Fourth, we examine the disservices resulting from forest restoration and the various approaches to value ES. Fifth, we discuss restoration across time and space. Followed by a conclusion that looks at further research opportunities.

7.2 The role of biodiversity

7.2.1 Biodiversity as a regulator or a final service?

The relation between biodiversity and ES is complex and multifaceted. Biodiversity influences ES at all levels: it regulates ecosystem processes and contributes to ecosystem resilience. On the other hand, biodiversity is also valued as a final service in the ES frameworks, as it is important for the conservation of threatened species and of gene pools and contributes to the aesthetic values of forests (Mace et al. 2012). We equate biodiversity here to specific counts of specific taxa. We identify four established ecological theories of Biodiversity Ecosystem Functioning (BEF) relationships, which predict that biodiversity has a regulating and supporting relationship with ecosystem functioning and can affect ES supply. First, niche complementarity theory predicts that diversity in the number and characteristics of species (i.e., trait diversity or functional diversity) should increase resource use efficiency, thereby improving ES supply (Tilman et al. 1997). Second, mass-ratio theory predicts that the most dominant species and their characteristics, rather than the diversity of species, determine ecosystem processes (Grime 1998). Third, structural diversity (such as tree density or basal area) also affects ES supply (Finegan et al. 2015). Fourth, the insurance theory predicts that species respond differently to environmental changes: performance decline in some species may be offset by increases in others; thus, a species-rich community insures long-term ecosystem functioning under environmental change (Yachi and Loreau 1999). Only a few studies quantify biodiversity's contribution to forest carbon stocks and cycling (van der Sande et al. 2017); the role of biodiversity in supporting other ES remains unclear. Many studies indicate that restoring a portion of original biodiversity suffices to restore a diverse range of ES (Lamb 2018) and increase the chances of restoration success (Aerst and Honnay 2011), while a meta-analysis shows only a weak and variable role of biodiversity (Carrick and Forsythe 2020).

7.2.2 How restoration affects biodiversity

During restoration, local biodiversity and forest structure can be recovered by a variety of restoration methods (Figures 7.2 and 7.3). Natural regeneration is the process by which forests regrow from seeds and diaspores that arrive and germinate in situ, or through vegetative growth from preexisting cover or rootstock. It does not require active tree planting but does require seed sources (e.g., nearby forests) and dispersal

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possibilities (e.g., birds). If these conditions are in place, natural regeneration has an advantage over active planting because of its low costs and because it promotes local species, which are usually native and locally adapted (Chazdon and Guariguata 2016; Crouzeilles et al. 2019). Natural regeneration success depends on conditions (Figure 7.1). Meta-analyses show that the biodiversity in natural regeneration is more similar to that of old-growth forests when past disturbance was less severe (Jakovac et al. 2021). Tree species richness recovery can be surprisingly fast, as little as five decades (Poorter et al. 2021a; Rozendaal et al. 2019), while recovery (to 90% of old growth forest values) of tree species composition may take centuries (Poorter et al. 2021a). Non-plant functional groups essential to ecosystem functioning vary in recovery time: while soil biota can recover in less than two decades, fungi and lichens can take a century or two (Spake et al. 2015; Teixeira et al. 2020).

Natural regeneration is unlikely to be effective in heavily degraded areas or when local seed sources are unavailable (César et al. 2021; Lohbeck et al. 2020). In such cases, more active forms of natural regeneration might be more suitable, such as assisted natural regeneration (ANR), where some species are liberated of competing vegetation to kickstart regeneration. Uebel et al. (2017) found a fourfold-increase in native tree and shrub species richness compared to non-assisted regeneration sites. Similar results were found for applied nucleation (where only parts of an area are planted: "tree island planting"); experiments show that tree density and diversity is consistently higher in areas treated with applied nucleation compared to sites without (Corbin and Holl 2012). Farmer Managed Natural Regeneration (FMNR) is ANR that occurs on active agricultural land, a form of agroforestry (Lohbeck et al. 2020; Rinaudo 2007). FMNR traditionally occurs in the West African Sahel; although quantitative evidence on what ES are restored remains sparse, there is evidence FMNR contributes to on-farm regional diversity and services with direct benefits to farmer livelihoods (Chomba et al. 2020; Moore et al. 2020).

Enrichment planting is a means to overcome potential barriers to natural regeneration such as absence of seed sources or dispersal agents. Seeds or seedlings are planted in forest gaps, young secondary forests, and other sites to improve and recover biodiversity (Lamb et al. 2005). Enrichment planting often focuses on selected species that provide food, timber, or other raw materials or that improve soil properties. Such useful species could help maintain the system, as it improves how restoration is perceived; yet overall biodiversity could decline if few species are planted and/or if they are already present in the system and become more dominant.

Sometimes more drastic interventions are needed such as "restoration plantations" (Figure 7.2). A study of rehabilitation of former bauxite mining lands in the Brazilian Amazon compared natural forest regeneration, mixed commercial species plantings of mostly exotic timber trees, direct seeding with mostly native, early successional tree species, and mixed native species plantings of more than 70 tree species (Parrotta and Knowles 1999). Basal area developed best in the mixed commercial species plantations, but these were relatively poor in species richness compared to the other treatments. Interestingly, all treatments were structurally diverse, which is important for providing habitats for mammals and other animals (Deere et al. 2020). The mixed native species plantations had a lower risk of arrested succession compared to natural regeneration in this case, likely because natural regeneration was slowed by vines and

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grasses. Planting native species overcomes this while also providing a broad range of benefits, such as recreating linkages and showing natural succession dynamics (McNamara et al. 2006).

Agroforestry can restore biodiversity by planting useful tree species in annual cropping systems (Ordonez et al. 2014). However, agroforestry species planted often differ from the native forest species composition. A global meta-analysis shows that forest species richness (including trees, epiphytes, and forest animals) is significantly higher (46%) in more natural agroforestry systems compared to more intensively managed coffee/cacao plantations (De Beenhouwer et al. 2013). Similar diversity increases can be found in silvopastoral systems when native trees and shrubs are integrated in the system (Broom et al. 2013; Murgueitio et al. 2011).

In some cases active restoration efforts have a negative effect on the desired outcome (Coleman et al. 2021). For example, in the Andes *Alnus acuminata* (Andean alder) is often planted to restore forests; after 30 years, such areas have lower alpha and beta diversity compared to naturally regrown secondary forests of the same age (Murcia 1997). Furthermore, the planting technique may also negatively impact restoration success: the use of heavy machines to plant trees causes damage to naturally resprouting individuals (Sampaio et al. 2007). These examples show that there are different trade-offs to active and passive approaches (Holl and Aide 2011). Biodiversity can recover through forest restoration. A global review found that restoration has positive impacts on both biodiversity and ES provisioning, especially in the tropics (Rey Benayas et al. 2009). Plant and animal species abundance can recover quickly and completely, but diversity recovers more slowly. Recovery is slower in the tropics than

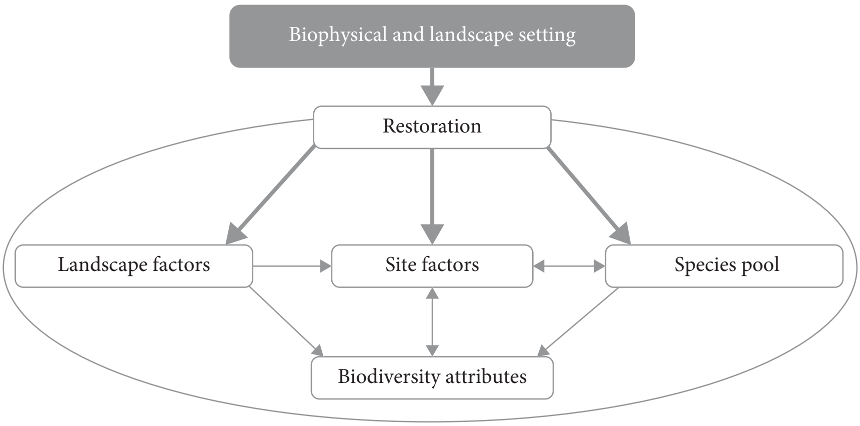

Figure 7.3 Conceptual model of biodiversity restoration. Restoration trajectory at a given site departs from the local biophysical and landscape setting (top box). Restoration might directly manipulate local site, landscape, or species pool (bold arrows). Biodiversity attributes, in turn, may be affected by local site, landscape, or historical factors that may or may not be directly influenced by restoration (light arrows). Biodiversity attributes can be defined at the taxonomic, functional, or structural level. Species pool and biodiversity attributes could also change site factors.

in temperate zones, possibly because a larger fraction of species was initially lost in the former (Meli et al. 2017). Moreover, the onset and speed of recovery of forests depends on climatic water availability (Poorter et al. 2021b). These generic results need to be interpreted cautiously because succession effectiveness depends on local context (Jakovac et al. 2021).

7.2.3 Native or exotic species?

In restoration, native species are generally preferred over exotic species. Justifications include their adaptation to the local environment and tendency to better support local biodiversity (Lamb et al. 2005). Wang et al. (2019) show that native forests support the highest overall diversity of arthropod species, followed by native/exotic mixed-species plantations, while exotic monocultures gave the lowest levels of support. A recent global synthesis of restoration approaches shows that carbon storage, water provisioning, erosion control, and biodiversity benefits are all supplied better by native forests, and that less complex (plantation) systems in dry regions supply these ES relatively poorly (Hua et al. 2022). Yet, conservationists argue that species should be assessed on their environmental impact rather than their origin (Davis et al. 2011). If environmental conditions have changed so significantly that an alternative state of the ecosystem is inevitable, then exotic species might facilitate the development of a novel ecosystem that better sustains ES provisioning (du Toit and Pettorelli 2019).

Local climate change might result in exotic species performing better than native ones (e.g., in response to drought). There are productive and fast-growing exotic species that are good at stabilizing soils and can help start succession (Vásquez-Castro et al. 2021). The danger is if exotic species become highly abundant and if they are functionally similar to co-occurring native species, then they risk becoming invasive (van der Sande et al. 2020). In summary, there are different risks to using native and exotic species in restoration, and careful species selection and studying their interaction with the environment is advised.

7.2.4 Diversity of biodiversity goals

People value different aspects of biodiversity and prioritize different services. Biodiversity goals for forest restoration take various forms; to evaluate success, it is important to define goals. These decisions have implications for what type of restoration interventions are used, and whether and when such efforts can be considered successful. Species richness, for example, is not always prioritized; aiming for full recovery of old-growth forest tree species richness can take over a century (Rozendaal et al. 2019). Some old-growth systems are naturally species poor and characterized by local endemics. In such cases, introducing new tree species will increase local diversity but threatens the uniqueness of the system. When restoration aims to support selected focal species, this can require keeping the system in a specific state that may not be the most diverse. For instance, restoring Dutch heathlands, a nutrient-limited

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ecosystem in a state of arrested succession, requires removing regenerating trees and intervening (e.g., controlled burning) to remove nutrients and unwanted grasses (Aerts and Heil 1993). Another example is the pied tamarin (*Saguinus bicolor*), one of the Amazon's most endangered primate species, which only occurs in highly degraded forest patches and city parks in central Manaus, Brazil's largest city in the Amazon forest. Maintaining a minimum habitat quality in these degraded forest patches and creating corridors between them is crucial for the conservation of this rare species, but aiming for the full recovery of these forest patches is unrealistic in this city forest (Barr 2016). As biodiversity and ES are closely linked, so are their goals.

7.3 Recovery of ecosystem services by means of forest restoration

7.3.1 Forest restoration, hydrological cycle, and water supply

Forests provide multiple functions and processes related to Earth's hydrological cycle, for example, by intercepting rainfall or mist (horizontal precipitation), and facilitating the infiltration and recharge of groundwater. Freshwater supply is a vital ES for all humans and other organisms; providing freshwater access is an important SDG. Maintaining freshwater supply is increasingly difficult; future estimates about global freshwater demand and supply are alarming. The UN World Water Development Report states that 3.6 billion people live in areas that suffer water scarcity at least one month per year, and that nearly 6 billion people will suffer from clean water scarcity by 2050 (WWAP/UN-Water 2018). Forest restoration changes the water dynamics both on the macro-level (i.e., between land surface and atmosphere) and micro-level (i.e., between soil and vegetation) (te Wierik et al. 2021) (Figure 7.4). The various mechanisms by which trees influence water availability remain only partly understood, but significant advances have been made in the last few decades. Until recently it was commonly accepted that increasing tree cover reduced local water availability we know now it is more complex (Ilstedt et al. 2016). A recent modeling study shows that sustainable reforestation in Europe will lead to increased summer precipitation (Meier et al. 2021).

In the past decade, significant advances have been made in understanding the effects of tree cover on the water cycle, especially the effect of increasing tree cover, an essential part of forest restoration. A systematic review on water yields after tree planting by Filoso et al. (2017) show that while most studies reported decreases in water yields following restoration, other studies observed hydrological benefits. They found that relatively few of the studies focus specifically on forest restoration, and fewer still assess the effect of native species; there is also a lack of large spatial or temporal-scale projects. Information is especially limited for the humid tropics and subtropics and is often context-specific. Many studies focus on the relationship between tree cover and groundwater recharge (Ellison et al. 2017; Ilstedt et al. 2016). Until recently, a commonly accepted theory was, simply put, more trees means less water. This theory is mainly based on case studies in plantations. The optimum cover theory has recently been proposed (Ilstedt et al. 2016), suggesting there

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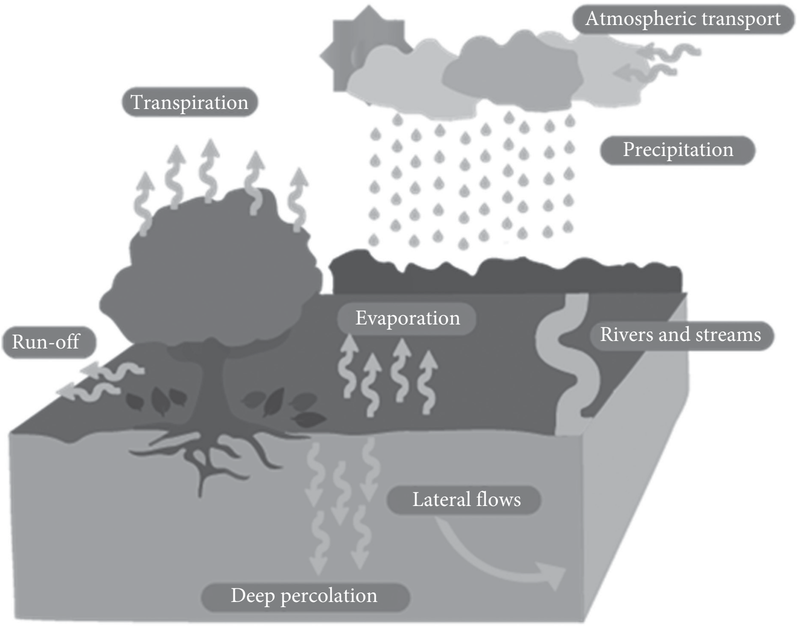

is an optimum for maximizing groundwater recharge, especially in the dry tropics (Table 7.1). A study in Burkina Faso shows that in treeless areas about 8 mm of precipitation per year recharged groundwater, but that for areas close to trees, groundwater recharge increased up to 39 mm due to improved soil infiltration capacity (Tobella et al. 2014). This capacity increased because of the presence of roots and soil fauna, which create macropores that act as water channels. This effect was observed up to 25 m away from tree stems, that even just a few trees per hectare can substantially improve groundwater recharge and reduce runoff. Other studies confirm there is an optimum in tree cover for groundwater recharge, but that it may result in less streamflow (van Meerveld et al. 2021). A study by Zimmermann et al. (2013) similarly found that where entire catchments undergo forest regrowth, there may be a substantial decrease in streamflow in the initial stages. Another comparison between a forested catchment and pasture catchment in Panama shows there was 35% less total runoff, smaller peak runoff rates and increased streamflow in dry periods in the forested catchment (Ogden et al. 2013). The effect of optimum tree cover on groundwater recharge in all these studies depends not only on improved soil properties but also on increased evapotranspiration through trees; combined, there still was a net positive effect. In another configuration (e.g., nonoptimal tree coverage) the result could be different.

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Table 7.1 Effects of forest restoration on water cycling related ecosystem characteristics. Effects of an increase in tree cover and management practices are shown. The icons in the first column provide information on the scale of the effect of restoration on an ecosystem characteristic. Management effects refer to any restoration interventions, including selection of species with certain traits. The biodiversity effect is the product of the latter and to what extent certain species are promoted over others.

Ecosystem characteristics	Effects and influences of characteristic	Restoration and management effects
Infiltration	Water entry in the soil, controlling surface runoff and recharging groundwater.	*Tree cover effect* = ↑ *Management*: tree spacing; soil management.
Groundwater recharge	Water moves downward from surface water to groundwater through the soil.	*Tree cover effect* = ∩ *Management*: species selection based on root system; soil management.
Transpiration	Trees extract water from the soil or groundwater and transpire it to the atmosphere as vapor through their stomata in their leaves.	*Tree cover effect* = ↑ *Management*: species selection based on crown type and leaf traits; pruning.
Interception	Interception of water by trees, leaves and other structures, preventing it from reaching the ground (and evaporating ultimately).	*Tree cover effect* = ↑ *Management*: species selection based on crown type and leaf traits; promoting complex forest structure to increase interception.
Soil evaporation	Evaporation from soil surface, the barer the soil, the more evaporation. Vegetation cover can prevent this.	*Tree cover effect* = ↓ *Management*: understory management, soil *Management*; selection of fast-growing species to cover the soil.
Surface runoff	Water leaving the system, running off the surface downstream. Bare soil increases runoff and stimulates soil erosion.	*Tree cover effect* = ↓ *Management*: understory management, soil treatments to decrease compaction; selection of fast-growing species to cover the soil.
Vapor and cloud capture	Interception of fog and cloud provides significant amounts of moisture in certain locations/seasons. Some plants extract water from humid air or water condensates on their leaves.	*Tree cover effect* = ↑ *Management*: species selection based on crown type and leaf traits; promoting more complex forest structure to increase the cloud intercepting surface.

(*continued*)

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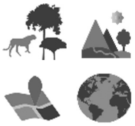
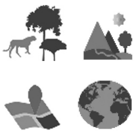
Table 7.1 Continued

Ecosystem characteristics	**Effects and influences of characteristic**	**Restoration and management effects**
Rainfall recycling 	An integrated property that results from many of the others, inside forest communities but also influences global atmospheric flow.	*Tree cover effect* = ↑ *Management*: not only forest type, but also density and structural complexity.
Biotic pump 	The theory that suggests that tree cover attracts atmospheric flows from elsewhere by favoring condensation to occur more frequently (a process that leads to lower air pressures).	*Tree cover effect* = ↑ *Management*: landscape management and planning, which impacts flow of air mass.
Flood moderation 	An integrated property that results from many of the others, tree cover allows for maintaining water longer in the system and releasing it more gradually which prevents floods.	*Tree cover effect* = ↑ *Management*: species selection based on root system; soil treatments such as gullies and barriers.
Water purification and fresh water supply 	Forests filter sediments and other pollutants from the water in the soil before they reach a water source, such as a stream, lake, or river.	*Tree cover effect* = ↑ *Management*: species selection based on root system; soil treatments that affect soil structure.

Legend:
Icons represent the **scale** of the effect.

tree level community level landscape level regional level global level
and the **direction** of the effect (**↑ increase, ↓ decrease, or ↷ here optimum).**

Other factors such as terrain, slope, amount of precipitation, previous and current land use, time, and species could affect groundwater recharge. For example, species with deep roots are able to connect the deep soil and groundwater with the atmosphere; the presence and number of deeply rooted species thus affects the water cycle (Fan et al. 2017). Much remains unknown about groundwater recharge, and optimal configurations are context- and location-specific.

It is increasingly recognized that much precipitation depends on moisture emitted by trees through evapotranspiration (te Wierik et al. 2021), yet there is still high uncertainty on where the tree-based moisture will fall as rain. Forest cover increases evapotranspiration, which can affect precipitation thousands of kilometers downwind

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on other continents (Sheil 2018; Van Der Ent et al. 2010). Though climate modelers still have difficulty simulating and predicting rainfall patterns in a consistent manner, most suggest that large-scale deforestation will reduce downwind precipitation, whereas maintaining or increasing forest cover can mitigate this reduction (Lawrence and Vandecar 2015). Recent empirical work confirms that deforestation negatively affects the hydrological cycle (Leite-Filho et al. 2021). Precipitation interception by the canopy might increase rapidly during forest succession and forest restoration; in as little as a decade throughfall volumes can approach typical mature-forest levels (Zimmermann et al. 2013). This could be explained by the theory that increased tree cover means intensified recycling of precipitation over land. More trees improve the recycling of this water, allowing it to evaporate and fall over land multiple times before it reaches the ocean again (Staal et al. 2018). The feedback between precipitation and tree cover has become an important focus for study. One recent theory, the "biotic pump," explains how tree cover influences pressure gradients that carry winds and moisture across continents; forest restoration could recover local moist climates and could bring back more reliable rainfall to drought-prone regions (Makarieva et al. 2013; Sheil and Murdiyarso 2009).

7.3.2 Forest restoration and nutrient cycling

Nutrient cycling has direct influence on local and global biogeochemical cycles and plays an important regulating and maintenance role in the provisioning of other ES. Many life forms depend on healthy soils. Fertile soils facilitate the production of food, timber, and other raw materials that people use daily. Humans obtain over 98% of their food from terrestrial lands; maintaining soil fertility is of great importance for human welfare (Pimentel and Burgess 2013). Forest cover typically plays an important role in maintaining the nutrient cycle (Figure 7.5), as forests can better retain soil and nutrients, and prevent runoff and leaching when compared to more open landscapes. Mineralization and leaf litter decomposition are the most commonly studied processes related to nutrient cycling in forests (de Bello et al. 2010); many other aspects, such as the interaction between soil fauna and vegetation, remain incompletely understood. Experiments show that the soil community is an important driver of forest restoration and can steer the direction of plant community development (Wubs et al. 2016). Forest restoration, for example, after intensive agricultural land use, can affect degraded soils by improving water infiltration, thereby preventing erosion and retaining nutrients.

A global meta-analysis of restoration of ES in tropical forests found that restoration activities contributed to a significant increase in soil nutrient attributes (Shimamoto et al. 2018). Recent evidence shows that on some abandoned agricultural fields and pastures, certain soil attributes (bulk density, carbon (C), and nitrogen (N)) recovered to 90% of old growth forest values in less than one year (Poorter et al. 2021a). In other cases, however, recovery took longer, for example, in Ghana after soil compaction from logging extraction machinery (Hawthorne et al. 2012). Recovery of other nutrient stocks may take longer as the soil gets extra nutrients from dying and

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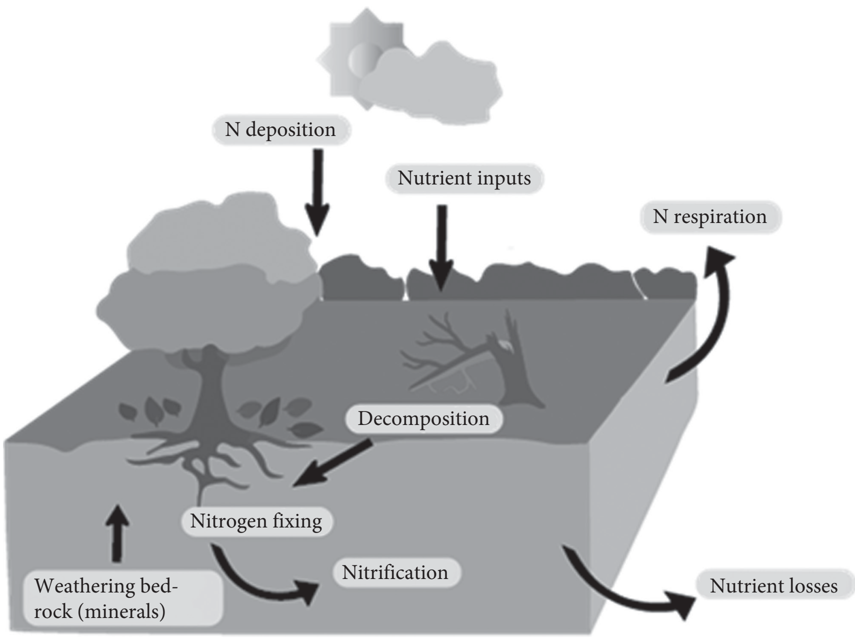

Figure 7.5 Representation between forests and nutrient cycling. Nutrients enter the forest ecosystem through deposition and by weathering bedrock. Within the system, nutrients are cycled through nutrient uptake by organisms and decomposition processes. Some trees form a mutually beneficial symbiotic relationship with soil bacteria that allow them to fix nitrogen. Microbes also facilitate the nitrification processes. Nutrients leave the system through leaching and respiration.

decomposing trees at later successional stages (van der Sande et al. 2022). Some people apply burning (e.g., in shifting cultivation) for a short-term increase in nutrient availability.

Soil recovery is strongly dependent on context. A recent analysis of 21 sites across the Neotropics shows that during secondary forest succession, bulk density decreased and C and N increased in forest regrowing on croplands and sites with high-activity clays; sites with annual lower precipitation generally decreased in pH, whereas sites with higher precipitation were more likely to show increased N and decreased C:N ratio (van der Sande et al. 2022).

Many studies show that live and dead biomass stocks can recover to mature forest levels within two or three decades. Soil functions and properties, however, do not recover as quickly. Soil recovery is positively linked to biomass increase (Gavito et al. 2021; Lohbeck et al. 2018); litter production and decomposition, are positively linked to standing vegetation biomass and are important aspects of restoring the nutrient cycle (Lohbeck et al. 2015). Organic matter can mediate key soil characteristics such as nutrient stocks and water-holding capacity (Larney and Angers 2012). Increasing soil organic matter through management and restoration measures could improve

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many other soil properties. Chen et al. (2020) show in a global meta-analysis that both soil organic C content and stock are on average 5% and 8% higher, respectively, in species mixtures than in monocultures. However, a study on riparian forest restoration in California, USA, found that soil carbon, N stocks and availability, and nutrient-use efficiency were not at mature forest levels after two decades (Matzek et al. 2016). Reforested sites might look similar to mature forests in terms of vegetation structure and biomass, but they do not function the same.

Soil function recovery is greatly influenced by prior land use (Jakovac et al. 2021). Gomes and Luizão (2012) show that previous land use, time since abandonment, and number of fire events explained 10–38% of the variation in the amount and configuration of soil macronutrients. The effect of prior land use varies with climate zones. In boreal forests it took soil 30 years to return to pre-disturbance soil C levels (Norris et al. 2009), while in secondary tropical forests it took 20–100 years (Martin et al. 2013).

Moreover, different restoration approaches return different results. A Costa Rican study of agricultural landscapes compared differences in litter production and macronutrients (C, N, Ca, Mg, P, Cu, Mn, and Fe) between natural regeneration, tree island plantations, patch plantations, and reference forests (Lanuza et al. 2018). They planted four species, of which two were N-fixing. After a decade, litter production and macronutrients did not differ between tree islands, patch plantation, or reference forests; however, all were greater than natural regeneration. In another study of agroforestry systems with multiple species, soil erosion rates were 50% lower than in monoculture systems (Muchane et al. 2020). This was probably due to through improved infiltration rates, reduced runoff, increased soil macro-aggregate proportion, and improved soil stability. What species are present, their characteristics and diversity, affects functions such as production, litter decay, and nutrient cycling (Hooper et al. 2005; Lohbeck et al. 2015). A meta-analysis of a large forestation program in Northern China illustrates that depending on the species, different soil attributes can be recovered (Gao and Huang 2020): one Pinus sp. increased soil organic C, while another increased total N content; a Robinia sp. was more effective at increasing available potassium content. In an experiment with 14 tree species, 30 years after establishing single-species plots, differences in litter calcium concentrations resulted in significant changes of soil chemistry and fertility (Reich et al. 2005). Other studies have similar results: certain pioneer species affected N availability and cycling more than others (Gomes et al. 2012); that native broadleaf species increased nutrient cycling more compared to exotic coniferous species (Ramírez et al. 2014), and that abundance of invasive species was a native broadleaf species increased nutrient cycling more than exotic coniferous species (Ramírez et al. 2014); and invasive species abundance is a good indicator for soil erosion restoration in degraded agricultural landscapes (Lohbeck et al. 2018). A study in China shows that plantations with only N-fixing species, after 25 years, resulted in 40–50% higher soil organic matter and 20–50% higher N concentration compared to non-N-fixing forests (Wang et al. 2010). In a 300-year chrono sequence in Panama, N-fixing tree species in young forests accumulated C up to nine times faster than non N-fixing species and showed species-specific differences in the amount and timing of fixation (Batterman et al. 2013).

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These results mean that some species are more efficient than others at restoring the nutrient cycling processes in degraded lands, especially as species selection is an important aspect for forest restoration practitioners and since species selection is one of the easier restoration measures to influence. Interestingly, some studies report that prior to restoration often no soil indicators were analyzed, highlighting a gap in soil data and project preparation (Mendes et al. 2019). This can be problematic: while the manipulation of physical, chemical, or biological components of the soil system can benefit site restoration, it can also have unintended cascading effects on other (soil) ecosystem functions and processes (Heneghan et al. 2008). It is important to use a holistic approach when defining restoration goals, one that includes all aspects of soil, vegetation, and their interactions. Table 7.2 provides an overview of forest restoration's effects on nutrient cycling characteristics.

7.3.3 Forest restoration, tree-based resources and provisioning services

Forests and trees provide vital resources for 1.3 billion people, of which 300–350 million people (about half of whom are indigenous) living within or close to dense forests depend almost entirely on forests for subsistence (FAO and UNEP 2020). Forests and trees provide a wide range of materials, both timber and non-timber forest products (NTFPs). For instance, about 50% of arboreal species in lowland Amazon are classified as useful species (Coelho et al. 2021). The World Bank forecasts that global timber demand is set to quadruple by 2050, emphasizing the need for plantation forests and the inclusion of timber species in restoration efforts. Many NTFPs are used and traded locally and globally. Most forested regions produce resins, nuts, fruits, fibers, medicinal and ornamental plants, animal foods, and other products. Indigenous peoples especially have vast local ecological knowledge on useful species. A field study in East Kalimantan among traditional forest-dwelling communities shows that at least 1,457 plant species are being used combining 2,141 distinct uses or values (Sheil et al. 2009). Many people worldwide, particularly those living in extreme poverty, depend on forest products (Angelsen et al. 2014). Meeting these people's basic needs should receive sufficient emphasis in restoration (see Kaimowitz and Sheil 2007). While the demand and the trade of many products is increasing, the provisioning of many products is declining as a result of deforestation, forest degradation, and unsustainable exploitation practices. This unbalance leads to increased concerns about the long-term sustainability of these products and the species from which they are derived.

There is ample evidence of the declining supply of forest products, exacerbated by unsustainable extraction practices over recent decades (Arnold and Pérez 2001; Bongers et al. 2019). The global food system plays a large role in environmental degradation and forest deforestation. Restoration can assist in maintaining, even increasing, the supply of forest products, for example, through (enrichment) planting, assisted regeneration, and species management (Box 7.1). Many useful and often underutilized tree and plant species offer the potential for sustainably produced foods, providing livelihood benefits, including improved human nutrition and multiple other ES (Jansen et al. 2020).

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Table 7.2 Effects of forest restoration on nutrient cycling-related ecosystem characteristics. Effects of an increase in tree cover and management practices are shown. The icons in the first column provide information on the scale of the effect of restoration on an ecosystem characteristic. Management effects refer to any restoration interventions, including selection of species with certain traits. The biodiversity effect is the product of the latter and determines to what extent certain species are promoted over others. See legend in table 7.1 for explanation of the icons.

Ecosystem Characteristics	Effects and Influences of Characteristics	Restoration and Management Effects
Nutrient uptake	Nutrient uptake influences plant growth and survival, affected by nutrient availability and tree traits.	*Tree cover effect* = ↓ *Management*: species selection based on relation with nutrient cycle (e.g., N fixers, mycorrhizal species).
Decomposition rate	Decomposition rate of plant biomass (e.g., leaves, trunks), is affected by tree traits, soil fauna, and microclimatic conditions.	*Tree cover effect* = ↑ *Management*: species selection based on wood and leaf traits; add decomposing bacterial/fungi packages; promoting high diversity of species to increase decomposition rate.
Litter quantity and quality providing soil protection and nutrients	Leaf litter quantity and quality is affected by plant and community productivity (this indirectly by plant nutrient uptake), tree traits and leaf characteristics. Litter is the basis for decomposition: food for decomposers, and provisioning of nutrients.	*Tree cover effect* = ↑ Species diversity effect = ↑ *Management*: species selection based on litter production and decomposability; promoting high diversity of species to increase quality and quantity.
Soil organic matter: stock and decomposition	Holding water and nutrients, providing nutrients after decomposition, providing food for decomposers (fungi, animals, bacteria).	*Tree cover effect* = ↑ *Management*: species selection, decomposition management.
Soil nutrient stocks; fertility	Soil nutrient stocks are determined by past land use, atmospheric nutrient deposition, weathering of parent material, rate of leaching, and vegetation type and tree traits.	*Tree cover effect* = ↑ *Management*: species selection; promoting high diversity of species to increase nutrient stocks.
N-fixing	Some tree species live in symbiosis with bacteria, which allows them to fix nitrogen from the atmosphere into usable compounds in the soil through a chemical process. The proportion of such species present in a community can affect the amount of N-fixing at the community level.	*Tree cover effect* = depends on species *Management*: planting or promoting species that have this characteristic.

(*continued*)

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Table 7.2 Continued

Ecosystem Characteristics	Effects and Influences of Characteristics	Restoration and Management Effects
Removal of material: • Timber • Fuel wood • Non-timber forest products (NTFPs) • Lopping and pruning 	All removal takes away nutrients out of the system. Removal in one system may decrease or prevent removal in another system, therefore removal of materials can have indirect effects on broad spatial ranges.	*Management*: control through regulations of what is and what is not allowed which affects the type of nutrients removed from the system (e.g., CITES – multilateral treaty to protect endangered plants and animals); sustainable management practices; proportion of useable species present in a community.

The supply of forest resources depends on forest production capacity (i.e., biomass production). This, in turn, depends on habitat and regulating functions. Maintenance of these ecosystem functions contributes to the (continuous) supply of forest and tree-based resources (Box 7.1).

The majority of tree plantations provide timber; a smaller portion produce fruit, resin, and other resources. Such plantations often consist of single species (monocultures), or a few commercial species (mixed plantations). Many of the (industrial) monocultures involve a limited number of species from a small number of genera, especially *Pinus*, *Eucalyptus*, *Tectona, Pseudotsuga*, and *Acacia*. These plantation forests are expanding to satisfy an increasing global demand for timber products.

There is an ongoing debate about whether monocultures can be considered forest restoration and what makes a forest a forest (see Chazdon et al. 2016). Monoculture plantations can supply large amounts of resources but hardly contribute to other forest restoration objectives (Hua et al. 2022). Moreover, they provide a very limited variety of resources compared to the variety found in original forests (e.g., bushmeat, medicine, and food). Studies show that plantations with two to four species can be more productive and have more advantages in biodiversity, economy, and forest health compared to monocultures (Liu et al. 2018). Careful design and planning are necessary in mixed plantations to combine trees with complementary traits that maximize positive and minimize negative interactions. Experience suggests that smallholders often prefer to include many tree species to diversify their production (Lamb and Gilmour 2005). Nonetheless, some smallholders participate in monoculture cash crop plantations such as oil palm. A household livelihood survey in multiple large-scale tree planting programs in India shows that tree planting supports little direct use by local people, indicating that large-scale tree planting does not take into account livelihood goals (Coleman et al. 2021).

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Box 7.1 Brazil nut trees in smallholder Amazon forest restoration

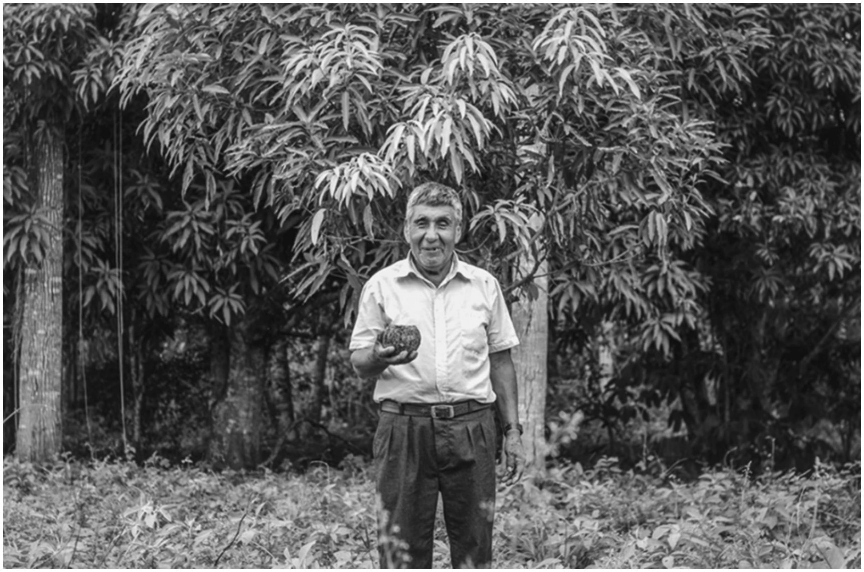

Figure 7.6 Photo: Rens Brouwer

The Brazil nut tree (*Bertholletia excelsa*, locally also called Amazon nut, Castanha or Castaña) is an emergent tree species occurring solely in the Amazon region. In many parts of the Bolivian, Peruvian and Brazilian Amazon forest, Brazil nuts are one of the more important NTFPs for rural livelihoods. Since the beginning of the 20th century, commercial exploitation of Brazil nuts has risen rapidly due to the import by Europe, the United States and other countries. This has led to Brazil nut being one of the few globally traded nuts that is harvested from natural forests (Guariguata et al. 2017). Although evidence suggests that these 'natural' forest have been domesticated for a long time. In most cases this product is harvested from 'natural' Brazil nut tree populations, unfortunately recent studies show that the sustainable production of Brazil nuts is threatened by lack of natural regeneration, adult tree mortality, and land conversion. An option to sustain the nut production and to maintain the presence of this emergent tree species in the Amazon rainforest is to enhance regeneration through enrichment planting or using this species in other types of forest restoration. In Peru local farmers, or castañeros (photo), have been actively and successfully planting this species on their land, mainly with a socio-economic incentive, but with forest restoration as an additional benefit. Secondary forests seem to be especially good locations to be enriched and restored with this species, adding value and incentive to protect these forests from future deforestation and further degradation (Brouwer et al. 2021).

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Market price differences means that an increase in low-value species lowers a plantation's economic value; yet, a greater diversity provides multiple benefits and services. There are intermediate restoration systems, such as the use of Eucalyptus as a transitional stage. Brancalion et al. (2020) show that biomass accumulation was nine times greater in mixed eucalypt-native species plantations compared to restoration plantations without the fast-growing eucalypt. Additionally, eucalypts did not affect the natural regeneration of native woody species before or after eucalypt logging in the stand. While both treatments had similar natural regeneration richness and planted non-pioneer growth, the income from eucalypt wood production offset 44–75% of implementation costs. The study shows how monocultures can aide forest restoration goals, and that intermediate transitional systems can provide multiple ES.

Natural regeneration has very diverse outcomes compared to monocultures, from species-rich forests to forests dominated by a few thriving species. Enrichment planting increases the populations of commercially important species in secondary forests (Lamb et al. 2005). Desirable species can be promoted through selective removal of competition and other silvicultural measures (Brouwer et al. 2021). FMNR allows farmers to enhance regeneration by managing certain species, mostly ones providing valuable resources (Lohbeck et al. 2020). Creating agroforestry systems with a mix of tree-crops, perennials, and annual plants is another intensive restoration method with high provisioning services output. Common perennial crops include mango, papaya, cocoa, coffee, rubber, and oil palm. Agroforestry systems have proven to be feasible tools for forest restoration and can achieve ecological and socioecological goals.

Species selection is crucial for restoring ES. Evidence shows that farmers prefer species that provide provisioning services (Cáceres et al. 2015; Heinze et al. 2020). Planting multi-purpose species can increase provisioning services while enhancing ecosystem function and biodiversity. The restoration of unproductive land with useful species is an important option to reduce the pressure on natural forests and to restore provisioning services. In Ecuador, for example, natural forests provide 120 timber species and many NTFPs for the market (Bendix et al. 2013); native tree restoration can help sustain the provision of these goods. More knowledge is needed on how restoration affects provisioning. An overview of the effects of restoration on provisioning ES is shown in Table 7.3.

7.3.4 Forest restoration and cultural services

Cultural services are different than the other ES. Cultural services provide mental, emotional, and physical benefits (MEA 2005). The most studied categories are recreation (e.g., ecotourism) and aesthetic values (e.g., artistic expression); less studied are cultural identity and heritage, as well as educational, spiritual, and religious values (Mengist et al. 2020; Schirpke et al. 2021). A recent meta-analysis found that 90% of 51 studies show at least one positive association between nature-based recreation and mental health (Lackey et al. 2021) (Box 7.2). In 2020, during the COVID lockdowns, there was a huge spike in daily forest visitors; many people turned to nature for recreation and relief (Derks et al. 2020). Psychological and social health, and other cultural services that can be linked to socioeconomic values, e.g., community economic

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Table 7.3 Effects of forest restoration on provisioning ES characteristics. Effects of an increase in tree cover and management practices are shown. The icons in the first column provide information on the scale of the effect of restoration on an ecosystem characteristic. Management effects refer to any restoration interventions, including selection of species with certain traits. The biodiversity effect is the product of the latter and determines to what extent certain species are promoted over others. See legend in table 7.1 for explanation of the icons.

Ecosystem Characteristics	**Effects and influences of Characteristics**	**Restoration and Management Effects**
Timber production	Presence or absence of species. Wood characteristics. Depends on the species selected, type of market (local vs international) and on market demand. Timber production demands some level of infrastructure, and through that also impacts on other issues (nutrient cycle, water cycle)	*Tree cover effect* = ↑⌒ bad for light-demanding species, good for slow-growing, old-growth species. *Management*: species selection, individual tree management towards high quality timber, reducing competition.
Non-timber forest products (NTFPs) production (food, medicinal, ornamental and raw material resources)	Presence or absence of species providing NTFPs. Depends on the type of product and intensity of collection. The impact depends on the part of the plant being collected (leaves, fruits), and varies from low (leaves) to high (roots).	*Tree cover effect* = ↑⌒ depends on proportion of usable species in a community. *Management*: species selection, planting and management, depending on the target products.
Genetic resources	Presence or absence of species with potentially useful genetic material "gene bank" (e.g., genes for resistance to pathogens).	*Tree cover effect* = ↑⌒ depends on species diversity. *Management*: selection for (genetic) diversity of species; control of dominating species.

development, are especially relevant in urban forests (Nesbitt et al. 2017). Forests are often connected to sacred natural sites, including particular trees and groves, that have a special spiritual significance for people and communities (Verschuuren et al. 2017). A study in Hawaii reveals how forests elicit spiritual, heritage, and identity-related values, and that these values vary with ethnicity and residence time (Gould et al. 2014). Sociocultural perspectives are not specific to cultural services, sociocultural

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Box 7.2 Shinrin-yoku, or forest bathing

The wind flowing through leaves, birds chirping, the scent of trees and dirt, the sunlight scattering through the leaves, fresh air. These are all things that we experience in forests and for many of us they make us feel at ease and in comfort. Our stress reduces, we are more relaxed, feel refreshed and get back our energy. Going to nature and forests to enjoy these benefits is something many people from different cultures do, but the Japanese even have a specific term for this: Shinrin-yoku. Shinrin in Japanese means "forest," and yoku means "bath", so it translates as 'forest bathing'. The term was coined by the head of the Japanese Ministry of Agriculture, Forestry, and Fisheries, Tomohide Akiyama, in 1982 to encourage more visitors to forests, later it grew out to a therapeutic practice. Studies have shown that forest environments reduce stress, anger, anxiety, depression and improve immune functions among participants (Li, 2010; Park et al. 2010). It is not a sport activity; it is about taking in the forest atmosphere to gain therapeutic benefits. In practice, you already gain these benefits during a leisurely walk, but some people also prefer to go to the forest with a more focused mindset to actively take a 'forest bath' by focusing on their five senses. Finding calmness and relaxation of course differs from person to person, but the presence of forests and trees allows people to have access to the benefits of forest bathing. Forest restoration can aid in providing these places or maintaining them. Especially restoring forests near cities could help to restore the connection between people and nature.

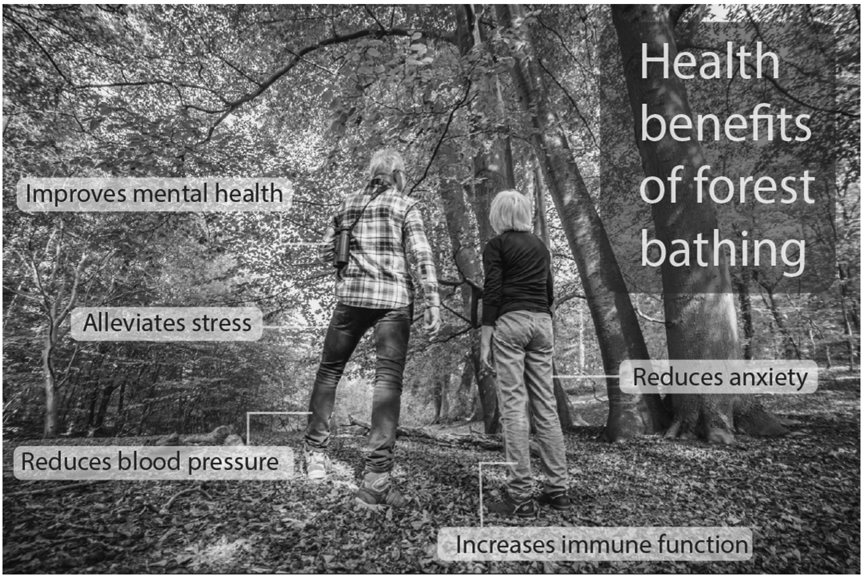

Figure 7.7 Photo: Rens Brouwer

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values show the importance that people and societies assign to a wide range of ES (Scholte et al. 2015). Understanding the cultural services gained by restoration projects could help capacity building and planning, and increase project support among multiple stakeholders.

The act of restoration in itself can be seen as a cultural service, in which people engage with nature for educational and inspirational purposes, giving some a sense of meaning (Bell 2001; Cramer 2008). Restoring urban and peri-urban forests enhances cultural services and well-being: people enjoy forests for the atmosphere and fresh air, relaxation and stress reduction, break from their hectic lifestyles, and emotional improvement (Hansen-Møller and Oustrup 2004; Schipperijn et al. 2010). Following a restoration project in the Atlantic forest of Brazil, people reported an appreciation for cultural ES such as aesthetic landscape improvement, tourism, recreation, as well as various religious, spiritual, and educational services (Brancalion et al. 2014). The support of local stakeholders in restoration projects increases the persistence of positive outcomes in the long term. FMNR, and likely other approaches that support local livelihoods, has the capacity to increase farmers' autonomy, which is an intangible cultural service (Moore et al. 2020).

Restoration does not necessarily mean all cultural services are improved. A survey in China shows that cultivated agricultural land and residential areas were evaluated as more important for providing cultural services than newly restored forests (Dou et al. 2019), probably because of local traditions of strong social neighborhood bonds in agricultural landscapes. Most interviewees believed that forest restoration had decreased religious and spiritual services, cultural heritage, and mental and physical health values. In contrast, aesthetic, recreational, inspirational, and education and science services were perceived as having increased in value after restoration. Forest restoration did not fit well in their current cultural values. This may be different for communities in landscapes where deforestation or forest degradation is more recent and where their cultural values are still somewhat centered around a forested landscape. Research on restoration effects on cultural services is scarce; most forest restoration research is focused on ecological aspects. An overview of the effects of restoration on cultural ES is shown in Table 7.4.

7.4 Trade-offs and disservices: One's gain can be another's loss

7.4.1 Trade-offs

Different restoration methods have different outcomes; even the same method can have different outcomes, depending on the former state of degradation and environmental conditions. Often there are trade-offs in the desired outcomes; there is no "silver bullet" method to restore all ES equally. Improving certain ES while supplying resources is difficult because trade-offs exist between forest product provisioning and ecological restoration (Lamb et al. 2005). Trying to achieve multiple goals can lead to hard choices and to compromises between conservation, biodiversity,

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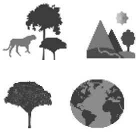
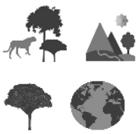
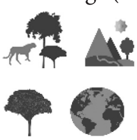
Table 7.4 Effects of forest restoration on cultural ES characteristics. Effects of an increase in tree cover and management practices are shown. The icons in the first column provide information on the scale of the effect of restoration on an ecosystem characteristic. Management effects refer to any restoration interventions, including selection of species with certain traits. The biodiversity effect is the product of the latter and determines to what extent certain species are promoted over others. See legend in table 7.1 for explanation of the icons.

Ecosystem Characteristics	Effects and Influences of Characteristics	Restoration and Management Effects
Recreation and maintaining mental and physical health 	Positive impact on valuation of nature, also outside the restored areas, people taking more care of nature, potential trickling down effects of these in (local) political decisions and economic choices.	*Tree cover effect* = ↑↷ high density will increase shelter but people also like parkland style with fewer but larger trees. *Management:* diversity of species can add to recreational values; structural and spatial diversification. Select species that do not commonly cause allergies.
Aesthetics 	Aesthetic quality of the landscape, based on (e.g., structural diversity, plant diversity, 'greenness,' tranquillity, presence of flowering plants, streams, etc.	*Tree cover effect* = ↑↷ create varying openness. *Management*: species selection; tree form; characteristics species; create structural diversity.
(Eco-)tourism 	Happiness, health, and volunteer involvement in restoration increases acceptance and importance.	*Tree cover effect* = ↑↷ depends on forest type and biome (e.g., savannas or forests are both valued touristic hotspots). *Management*: select species with a story (flagship species); select species that attract wildlife.
Natural heritage, sense of belonging, and traditional ecosystem knowledge (TEK) 	Intergenerational connection, Increasing care of nature "future of our children," sacred sites are being protected.	*Tree cover effect* = ↑↷ depends on historical forest cover, type, and biome. *Management*: highly diverse system increases connection and sense of belonging; opportunities of maintaining TEK through intergenerational connections; education, evaluation, and classification leads to valuation.

and production, which may result in suboptimal outcomes for each. Schwaiger et al. (2019) found a trade-off between increased productivity and decreased structural diversity in a production-oriented forest, and between improved groundwater recharge and loss in productivity in a multifunctional-oriented forest. Trade-offs in ES recovery can often be traced back to the species that were planted or regrew naturally.

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Zeng et al. (2019) found significant effects of tree functional groups on ES (in this case, plant diversity, air quality regulation, soil fertility maintenance, global climate regulation, and timber provisioning). In naturally regenerated forests, deciduous broadleaves had significant positive effects on the measured ES, whereas conifers and broadleaf evergreens had negative effects.

7.4.2 Disservices

Forest restoration can have negative impacts or "disservices." Forests can have some harmful characteristics: they are sources of pests, diseases, and disease vectors. Well-known examples are malaria, ebola, river blindness, hendra, and possibly COVID-19 (Dunn 2010). Recent wildfires around the globe have shown that forests can become fuel for such devastating natural disasters. Forests can negatively impact freshwater supply because trees use water (Ilstedt et al. 2016). Also, within the ES frameworks disservices can be found. ES are defined in relation to human needs; as people's values, preferences, and expectations vary, so do their perceptions of ES. Therefore, how ES are perceived can differ between groups of people or individuals. An example of differing values between groups is that rural and indigenous people value the forest because of the spiritual importance of sacred forests and their dependence on its natural resources, while urban groups often value forests for employment and tourism. Also, at the individual level, perceptional differences occur: the hiker likely appreciates a healthy forest high in biodiversity with many animals to spot, while a farmer sees that same forest on his land as a limiting factor in the amount of farmable land. A study in southwestern France shows farmers' mixed views on the (material and nonmaterial) contributions of rural forests (Blanco et al. 2020). According to the farmers, trees provide some beneficial services to agriculture (e.g., erosion control, windbreak) and some disservices (e.g., reduced crop yield, pest source). Multiple values and perceptions coexist; the difficulty is in addressing them together. It is key for restoration decision-making and for understanding restoration effects that the perceptions of all relevant stakeholder groups are taken into account (Constant and Taylor 2020).

Land users seldom share the same priorities in terms of where, when, and how to address restoration, and who to involve. It is important to understand how livelihoods interact with different restoration methods (Crossland et al. 2018). Unsurprisingly, conflicts arise when single services for a few users are targeted in isolation, when other stakeholder interests are neglected (Bullock et al. 2011). This can undermine restoration efforts and influence long-term sustainability. In addition, the value of other land uses and vegetation types should not be neglected; forest 'restoration' can threaten unique vegetation such as open grassland and savannas, which have biodiversity value as well (Veldman et al. 2015). In fact, tree planting on savanna ecosystems would be afforestation, but there is a worrisome tendency to frame all tree planting as restoration nowadays. Scientific studies might help map stakeholder needs, which can advise policymakers and governing institutions on how to make restoration attractive and inclusive for all stakeholders (Lamb 2018). A study in the Brazilian Atlantic rainforest, for example, shows that investigating perceptions of restoration benefits could help promote consensus-building among stakeholders (Brancalion et al. 2014).

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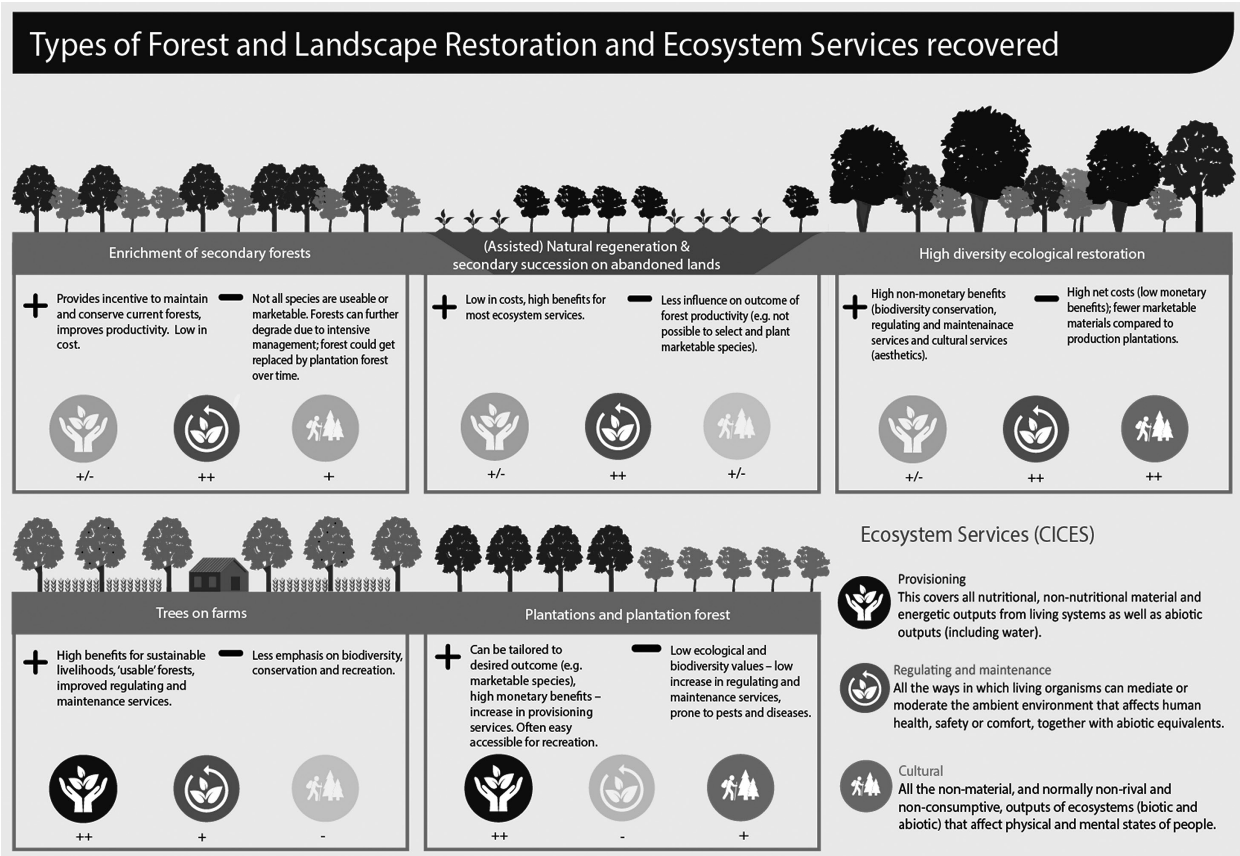

Infographic 7.1 ES provided by different forest restoration methods (also see Figure 7.2). The most common restoration methods are listed. (Infographic by R. Brouwer)

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Understanding the scale and harm of disservices in forest restoration activities is key for success.

7.5 Restoration across scales of time and space

Global goals aim to restore millions of hectares of (formerly) forested land, yet more and more land is needed to produce our food, along with many other goods. Since 1970, the harvest of commercial timber has increased almost 50% while the value of agricultural crop production has increased about threefold (FAO and UNEP 2020). Forest restoration competes for land with monoculture timber plantations and agricultural land use among others. Therefore, restoring forest on former agricultural land may result in the displacement of agricultural activity. Increased efficiency of agricultural production, reduced food waste, and a more socially just distribution of food can help balance food demand and reduce agricultural land demand, providing opportunities for forest restoration (Bajželj et al. 2020). Some services (e.g., carbon sequestration and timber production) might be most easily provided by large industrial plantations rather than many small farmers restoring forests on their lands. Restoring forests with a production goal might then displace smallholders and generate significant social costs (Lamb et al. 2005). It could also lead to forest degradation or deforestation in the regions to which these smallholders are displaced.

High-diversity restoration forests are difficult to implement at large landscape scales, while they could thrive on smaller local scales (Lamb 2018). This discussion is tightly linked to the intensive land sparing versus land sharing debate (Sidemo-Holm et al. 2021; van Noordwijk 2021). Restoration by land sharing has the potential to enhance ES and biodiversity on agricultural sites at both the field and landscape scales. On the other hand, restoration by land sparing would provide these benefits only at the restored site and not at the agricultural site; but when zooming out to the landscape scale there, would be an overall net gain in restored ES (Rey Benayas and Bullock 2012). In a study on this topic in agro-ecosystems, land sparing led to similar biodiversity recovery but higher ecosystem recovery than land sharing (Barral et al. 2015). Other studies show that crop production and revenue can be enhanced alongside forest restoration and biodiversity conservation without the loss of other ES in the same landscape (Cavender-Bares et al. 2015; Marcilio-Silva et al. 2018).

Besides differences in ES supply on a spatial scale, there are also differences on a temporal scale. The outcome of forest restoration changes over time, and the supply of ES (and their interactions) is often lower at the start of restoration than after a few decades. Many studies show that ES recovery takes time: on rehabilitated mine lands, for example, environmental indicators such as soil chemical properties and species composition increased over time (Gastauer et al. 2020). Others also show that more mature forests have a greater capacity to supply higher and more evenly distributed ES benefits (Liu et al. 2019; Zeng et al. 2019). Many community characteristics, including diversity and biomass production, vary intrinsically with succession and community history (Sheil and Bongers 2020). Moreover, the temporal trajectories of

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Table 7.5 Factors that drive variation in forest restoration outcomes. Source: adapted from Pickett et al. 1987

Factor	Processes or Aonditions Affecting Restoration Outcomes	Specific Characteristics of Factor
Local site and past land use	Disturbances, topography, climate, drainage	Type of past land use and disturbances, severity, frequency, resource availability
Time	Forest succession	Length of community development, length of past land use and disturbances
Species pool	Seed dispersal, resprouting ability, presence or absence of invasive species, type of species regenerating, types of species planted	Landscape configuration, presence of forest remnants and dispersal agents, remnant vegetation, prior vegetation, prior land use
Species traits	Functional and life history traits, ability to adapt to the current (changed) environment	Germination chance, establishment success, growth requirements, resource use
Species interactions	Intra- and interspecific species competition, diseases, herbivory, pollination, dispersal, defense mechanisms, mycorrhizae	Population size, structure and dynamics, recruitment, growth, mortality, trophic structure, facilitation
Human interaction with restored forest	Presence or absence of humans in restored landscape, use of restored forests	Policies, laws, enforcement, protection of restoration project, stakeholders' interest and needs, species usability

ecosystem structure and functions in restored ecosystems can, in some instances, be decoupled, which implies that the monitoring of restoration programs should include measurements of functions in addition to structural indices that can be remotely sensed (Ferraz et al. 2020).

Restoration happens across time and space; outcomes vary depending on multiple factors (Table 7.5). Before implementing a restoration intervention, it is important to map these factors' effects and the possible outcome trajectories.

7.6 Opportunities for further research and restoration projects

This chapter has summarized the known and expected effects of forest restoration on ecosystem characteristics. Despite the breadth of the literature, important geographic and thematic knowledge gaps remain. Our findings echo those of Howe et al. (2014), that is, the current literature focuses on particular geographic regions and individual ES and neglects trade-offs and synergies between ES. Current literature suggests that forest restoration bolsters biodiversity recovery, but that overall success is context-dependent. If restoration targets resilience, newly restored forests and their ES might

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be more resilient to future (climate) changes. Clearly, not everything is possible everywhere, but targeted measures can help achieve goals. Based on our evaluation, we suggest three research opportunities.

First, understanding the context of forest restoration activities is crucial to improving outcomes. Most studies focus on just a few regulating and maintenance services. A broader, multifunctional study approach is needed to identify trade-offs between ES in different forms of restoration.

Second, provisioning services and cultural services remain poorly represented in restoration projects. Balancing resource extraction such as timber production with other ES thus presents a challenge. Cultural services (e.g., recreation) are often neglected in restoration projects, despite being among the most tangible to local people. Provisioning and cultural services are both part of the socioeconomic benefits restoration provides. With good evaluation systems in place, these benefits offer a good opportunity for restoration research (Van Oudenhoven et al. 2012).

Third, very little research attention has been devoted to disservices. It is poorly understood how these (unintentional) restoration results balance with services, and how they differ between stakeholders. Clearly, the causes and impacts of disservices need more attention in restoration research (Grass et al. 2020).

Much can be gained through the effective communication of scientific results to stakeholders and the general public, in order to guide and inform restoration programs. One way to bolster interest and support from stakeholders is by targeting ES that are of sufficient interest to stakeholders.

Context matters in forest restoration projects. It defines appropriate methods, outcomes, and implications. Context is, by definition, created by different (potential) functions of restored forests. A broad, multifunctional focus in restoration is needed to identify and weigh services and disservices for them to be understood, and to evaluate total success. In addition, both short- and long-term goals need to be clear in order to design restoration projects that can succeed in changing circumstances. The generalized summary of studies in this chapter to evaluate restoration research can be helpful also in assessing the potential contribution of restoration projects to reaching SDGs and local societal goals and needs.

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