







UN DECADE ON ECOSYSTEM RESTORATION

REVIEW ARTICLE

Precision restoration: a necessary approach to foster forest recovery in the 21st century

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Forest restoration is currently a primary objective in environmental management policies at a global scale, to the extent that impressive initiatives and commitments have been launched to plant billions of trees. However, resources are limited and the success of any restoration effort should be maximized. Thus, restoration programs should seek to guarantee that what is planted today will become an adult tree in the future, a simple fact that, however, usually receives little attention. Here, we advocate for the need to focus restoration efforts on an individual plant level to increase establishment success while reducing negative side effects by using an approach that we term “precision forest restoration” (PFR). The objective of PFR will be to ensure that planted seedlings or sowed seeds will become adult trees with the appropriate landscape configuration to create functional and self-regulating forest ecosystems while reducing the negative impacts of traditional massive reforestation actions. PFR can take advantage of ecological knowledge together with technologies and methodologies from the landscape scale to the individual-plant scale, and from the more traditional, low-tech approaches to the latest high-tech ones. PFR may be more expensive at the level of individual plants, but will be more cost-effective in the long term if it allows for the creation of resilient forests able to provide multiple ecosystem services. PFR was not feasible a few years ago due to the high cost and low precision of the available technologies, but it is currently an alternative that might reformulate a wide spectrum of ecosystem restoration activities.

Key words: aerial unmanned vehicles, artificial intelligence, drones, ecological interactions, forests, remote sensing, seeding, sowing

Conceptual Implications

- Social and political interest for halting the impact of humans on nature is creating an opportunity to restore forests. However, for a successful restoration we need to give more attention to the fate of the planted or seeded individuals to ensure that they become adult trees.
- We advocate for a precision forest restoration (PFR) approach to increase forest restoration success. PFR should combine a wide spectrum of ecological knowledge, technologies, and methodologies from low-tech to the most high-tech currently available to increase the chances that each plant become an adult tree while minimizing costs and disturbance.
- PFR seeks the recovery of functional resilient forests at landscape level, but focuses on the biotic and abiotic limitations for establishment at individual-plant scale.

Introduction

Forests are increasingly recognized for their role as a nature-based solution to many of the challenges currently faced by humanity, such as the climate crisis, the biodiversity crisis, and pandemic risks (FAO 2020). Therefore, the goals of restoring degraded or heavily disturbed forests and reversing global

deforestation have an enormous social, economic, and political relevance today (Di Sacco et al. 2021). In this context, tree planting—either to restore native forests or to increase national and global tree cover—has received enormous attention, to the point that several impressive programs and commitments have been initiated to recover forests at global, regional, or national scales (Fagan et al. 2020; Holl & Brancalion 2020; Table 1). These commitments have lacked strict legal obligations so far, but in some cases they have been underpinned by strong political and

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Table 1. Summary of the main commitments and initiatives to restore ecosystems in large areas of the planet and that include, implicitly or explicitly, tree plantation. The table covers the majority of global restoration commitments under the Rio Conventions and unofficial initiatives, but it is not an exhaustive and systematic overview of all global pledges. The data in column “Restoration Committed” cannot be summed because there is an overlap between the conventions, global initiatives, and/or regional pledges. Adding up all the country commitments that have been submitted under the Rio Conventions and the Bonn Challenge or related regional initiatives provides a total global range of commitments from 765 million to 1 billion hectares (Sewell et al. 2020). The commitments data are extracted from sources expressed in hectares, area-based metrics translated into hectares, or number of trees. Commitments from private companies are not included. (a) United Nations Convention on Biological Diversity; (b) United Nations Convention to Combat Desertification; (c) United Nations Framework Convention on Climate Change; (d) United Nations Forum on Forest; (e) International Union for Conservation of Nature; (f) United Nations Development Program; (g) World Economic Forum; (h) World Wide Fund for Nature; (i) Wildlife Conservation Society; (j) United Nations Environment Program; (k) New Partnership for Africa’s Development; (l) United Nations Economic Commission for Europe; (m) Food and Agriculture Organization of the United Nations; (n) World Resources Institute. Sources: (1) <https://www.cbd.int/nbsap/>; (2) <https://knowledge.unccd.int/home/country-information/countries-with-voluntary-ldn-targets>; (3) <https://www4.unfccc.int/sites/NDCStaging/Pages/Home.aspx>; (4) <https://www.un.org/esa/forests/documents/un-strategic-plan-for-forests-2030/index.html>; (5) <https://www.bonnchallenge.org/>; (6) <https://infoflr.org/bonn-challenge-barometer>; (7) <https://ark2030.org/>; (8) <https://www.1t.org/>; (9) <https://trilliontrees.org/>; (10) <https://www.trilliontreecampaign.org/>; (11) <https://www.weforest.org/page/about-us>; (12) <https://edenprojects.org/mission-and-vision/>; (13) <https://onetreepanted.org/pages/about-us>; (14) <https://www.arborday.org/generalinfo/about.cfm>; (15) <https://treesisters.org/about-us>; (16) https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/actions-being-taken-eu/EU-biodiversity-strategy-2030_en; (17) <https://afr100.org/content/countries>; (18) <https://www.greatgreenwall.org/>; (19) <https://infoflr.org/bonn-challenge/regional-initiatives/ecca30>; (20) <https://initiative20x20.org/regions-countries>; (21) <http://www.fao.org/forestry/45685-0ad87e3a1d4ccc359b37c38fcb5b1fc.pdf>; (22) <https://regreeningafrika.org/>

Scale	Agreement or Initiative	Leader(s) Organization(s)	Commitment Regarding Restoration	Restoration Committed (Trees planted)	Source
Global	Aichi Biodiversity Targets	UNCBD (a)	To restore at least 15% of degraded ecosystems by 2030	90 million ha	1
	Achieving Land Degradation Neutrality	UNCCD (b)	To restore degraded land to achieve a land degradation-neutral world by 2030	450 million ha	2
	Paris Agreement	UNFCCC (c)	To conserve and enhance forest carbon stocks through sustainable management	250 million ha	3
	UN strategic plan for forests 2030	UNFF (d)	A 3% increase in forest area worldwide by 2030	120 million ha	4
	The Bonn Challenge	IUCN (e), UNDP (f), Government of Germany	To restore 150 million ha of the world’s degraded lands. Extended by the New York Declaration on Forests to 350 million ha by 2030	350 million ha	5, 6
	Ark 2030	Ark 2030	To restore 500 million ha of land across five critical landscapes	500 million ha	7
	1 Trillion Trees Campaign	WEF (g)	To restore and conserve 1 trillion trees globally by 2030	1 trillion trees	8
	Trillion Trees	WWF (h), WCS (i), Birdlife International	Ending deforestation and restoring forests in critical areas for the benefit of wildlife, people and a stable climate	1 trillion trees	9
	Trillion Trees Campaign	Plant for the Planet, UNEP (j)	To plant one trillion trees to fight the climate crisis	1 trillion trees (13.94 billion)	10
	WeForest	WeForest	To restore 25,000 ha of forests with 25 million trees	25 million trees	11
	Eden reforestation program	Eden reforestation	To plant a minimum of 500 million trees each year until 2025	(1 million)	12
	One Tree planted	One Tree Planted	No commitment	(4 million)	13
	The Arbor Day Foundation	The Arbor Day Foundation	No commitment	(350 million)	14
	Tree Sisters	Tree Sisters	To plant 1 billion trees annually	(12 million)	15
Regional	EU Green Deal/ Biodiversity Strategy	European Commission	To plant 3 billion trees by 2030	3 billion trees	16
	AFR100	NEPAD (k), African Union	To restore 100 million ha of degraded land in Africa by 2030	100 million ha	17
	Great Green Wall	UNCCD, African Union	To restore 100 million ha of degraded land across the Sahel region by 2030	100 million ha	18
	ECCA30	IUCN, UNECE(l), FAO (m), WRI (n)	Bring 30 million ha of degraded land in Europe, the Caucasus, and Central Asia into restoration by 2030	30 million ha	19

Table 1. Continued

Scale	Agreement or Initiative	Leader(s) Organization(s)	Commitment Regarding Restoration	Restoration Committed (Trees planted)	Source
	Initiative 20 × 20	17 national governments across Latin America and the Caribbean	To restore 20 million ha of degraded land in Latin America and the Caribbean by 2020	20 million ha	20
	Agadir Declaration	FAO	To restore 8 million ha of degraded land in the Mediterranean region by 2030 (endorsed by 10 countries)	8 million ha	21
	Regreening Africa	Regreening Africa	To reverse land degradation on 1 million ha by 2022 in Sub-Saharan Africa (endorsed by 8 countries).	1 million ha	22

economic investments in several nations.

A key point in all these programs is the focus on numbers—planting billions of seedlings with the aim of achieving millions of trees (Table 1). However, apart from putting effort into planting trees, it is important to think about how to ensure that the seedlings that we plant today will become trees several decades later. Maintenance of reforested sites is uncommon beyond a few months, affecting the long-term success of the restoration programs (Kodikara et al. 2017; Brancalion et al. 2019; Howe et al. 2020). The main commitments related to forest restoration strongly emphasize the economic activity that planting trees will generate and how this translates into jobs, green investments, and local livelihoods. These objectives are absolutely needed and praiseworthy, but to create ecological and economic richness and welfare we first need to focus on what we will get after reforestation, how to make sure that planted trees grow safely once past the seedling stage, and how to guarantee that the resources spent on restoration programs help to deliver the objectives that we expect from the moment the tree is planted. In summary, we need to focus on the efficiency of reforestation and forest restoration programs.

Efficiency is a central parameter in any human activity where the economy is involved, including agroforestry production, farming, and other activities of the primary sector (e.g. Kumar et al. 2020). However, it is rarely considered in forest restoration or reforestation programs. It is true that the efficiency of ecosystem restoration is hard to measure, especially when considering that restoration goals are characterized by long-term deployment and uncertainties, must respond to short-term “emergency” requests (e.g. following catastrophic disturbances), and that the efficiency itself should be evaluated with respect to ecosystem services whose biophysical assets and economic value are hard to define. However, improving efficiency should be of strategic importance for forest restoration—particularly if we seek to restore forests at such large and global scales—given its impact on resource investment, ecological success, and social acceptance (Higgs 1997).

The pressure for optimizing efficiency has even given rise to the development of new concepts revolving around the term “precision,” such as “precision agriculture,” “precision forestry,” or “precision fishery” (e.g. Srinivasan 2006; Fardusi

et al. 2017). Overall, these concepts seek to take advantage of novel technologies to increase the efficiency of their respective activities via the reduction of costs and increases in productivity and small-scale accuracy of all processes. Traditional forest restoration, however, differs greatly from this perspective. Although technology is present in reforestation activities, it is mostly devoted to the production of plants and to large-scale preparation of the planting site with heavy machinery (e.g. soil scarification, hole digging, postdisturbance management; Löf et al. 2016; Brancalion et al. 2019; Masarei et al. 2021), but with little consideration for microscale factors and the fate of seedlings once the plants are under field conditions. Such large-scale approaches may even create additional disturbances in the area to be restored, which may also translate into negative impacts on the ecosystem and on the restoration itself (e.g. Löf et al. 2016; Leverkus et al. 2021a).

Here, we advocate for the development and application of the concept of “precision forest restoration” (PFR), which we define as “a combination of knowledge, technologies, and methodologies from the landscape scale to the individual-plant scale to increase the success of each planted or sowed tree while minimizing the disturbance in the area to be restored.” The set of knowledge, technologies, and methodologies used may include a wide spectrum of practices, from the most traditional and low-tech of them to the latest high-tech advances (Table 2). Although a restoration program may include thousands of hectares and needs to work at large spatial scales, the focus of a precision restoration approach should be each particular seedling regardless of the spatial extent considered. Of course, the objective of forest restoration should be to create a healthy and functional forest ecosystem, and in this sense the ultimate focus should be the forest and its dynamic at a landscape scale. All of this is already discussed in other recent approaches for forest restoration, such as forest landscape restoration, the target plant concept, the framework species method, or the very concept of restoration ecology (SERI 2004; Stanturf et al. 2014; Dumroese et al. 2016; Florentine et al. 2016; Di Sacco et al. 2021). Our proposal of a PFR approach seeks to work in the same direction, but concentrating on the whole set of environmental factors (biotic and abiotic) that determine plant performance once the plants are facing field conditions. The PFR concept is inspired

Table 2. Summary of the main knowledge, technologies, and methodologies that can be used to overcome the problems associated with forest restoration success from a precision forest restoration approach for each of the five critical steps considered in this work.

<i>Step</i>	<i>Main Objective</i>	<i>Knowledge, Technologies, and Methodologies</i>
Site and species selection	To select appropriate species and seed sources. To find suitable planting or sowing niches from the macroscale to the individual plant scale. To delimit areas where natural regeneration makes planting or seeding unnecessary, or where natural regeneration can be managed to support forest restoration.	Local and expert knowledge on native communities. Classical vegetation maps. Species distribution modeling under current and forecasted conditions. Remote sensing: hyperspectral, multispectral, and RGB imagery obtained from satellites, manned and unmanned aerial vehicles (e.g. drones), or handed sensors, and airborne and terrestrial LIDAR. Digital elevation models. Habitat suitability and abundance models driven by high-resolution remote sensing data. Ecohydrological models. Network analysis and landscape connectivity modeling. Artificial intelligence (particularly machine learning and deep learning).
Site preparation	To improve microsite conditions (at individual plant level) for increasing establishment success.	Soil mechanical preparation. Hydrogels to retain moisture. Underground porous vessels with water. Organic amendments. Use of artificial shelters to reduce microclimatic harshness at individual plant scale. Inoculation with mycorrhizal fungi. Mulching (with different materials: straw, wood chips, gravel, etc.). Manual weeding. Localized herbicide application. Ecohydrological corrections at landscape level. Construction of microcatchments and other water runoff and air moisture harvesting systems at plant or microscale level.
Reforestation method: planting or sowing	To choose seedling planting or direct seeding according to species and site characteristics. Protection of seeds against seed predators may be necessary in case of direct seeding.	Technologies for appropriate seed production, collection, and processing (not considered explicitly in this summary). Technologies for production of quality seedlings in nurseries (not considered explicitly in this summary). Physical individual seed protectors. Seed coating with deterrents (chemical substances, odors from carnivores, etc.). Deep planting or sowing. Remote sensing and artificial intelligence to map appropriate seeding sites. Drones for high-precision direct seeding.
Promoting positive ecological interactions	To take advantage of positive ecological interactions that drive succession towards mature forests.	Promotion of seed dispersers' populations (corridors, perches, reintroductions, etc.). Concentration of efforts to recover remaining trees that act as seed sources. Use of nurse shrubs to improve microsite characteristics. Use of nurse structures and biological legacies to improve microsite characteristics. Remote sensing and artificial intelligence to get highly-precise maps of legacies that promote positive ecological interactions.
Postplanting care and monitoring	To ensure that seedlings become a reproductive tree.	Associational defense with nurse plants. Nurse structures that provide physical protection against herbivores (e.g. pile of branches). Use of treeshelters to reduce microclimatic harshness at individual plant scale. Fences (particularly small fences [dozens of square meters] or individual fences). Remote sensing and artificial intelligence to map protected microsites. Watering (application of emergency irrigations). Microwatering (subsurface localized micro-irrigation). Weeding. Field and remote sensing-based monitoring of seedling development, water stress, and soil moisture to guide plant care and adaptive management.

by the principles of precision agriculture in the sense that it seeks to increase efficiency and decrease environmental and economic cost (St-Denis et al. 2018). However, its focus is beyond short-term measurable economic profit, as the main goal should be to create healthy ecosystems with high resistance and resilience to disturbances that may resume their

maximal provision of ecosystem services of all kinds and function without further human intervention as soon as possible. Furthermore, a PFR approach does not rely exclusively on the application of cutting-edge technologies, but rather on the appropriate combination of low-tech and high-tech solutions to increase restoration success.

We seek to offer a summarized guide for the implementation of a PFR approach comprising five critical steps for the establishment of trees planted in the field as seedlings or seeds. These are: (1) site and species selection, (2) site preparation, (3) deciding between planting or direct seeding, (4) the promotion of positive ecological interactions that boost restoration, and (5) postplanting care (Table 2). Successful forest restoration also involves other key components, such as the removal of degradation factors if they persist in the target area, seed provisioning and handling, seedling production in nurseries, or social and legal aspects (e.g. Stanturf et al. 2014; Brancalion & Holl 2020; Erickson & Halford 2020; Di Sacco et al. 2021). Nonetheless, our proposal for a PFR approach will focus on the ecological principles that need to be considered to increase the success of each particular seedling once they are facing the complete set of environmental—and uncertain—field conditions. We assume, therefore, that restoration will occur in sites previously occupied by native forest avoiding undesirable afforestation, that the factors contributing to degradation are controlled, that plants or seeds have the required quality, and that social and legal aspects are properly considered. Our focus is the restoration of native forests, but the concept can be applied to any other field of ecological restoration. For simplicity, we will use the terms forest restoration and reforestation interchangeably.

Precision Forest Restoration

Step 1: Site and Species Selection

Once the area to be restored has been set, restoration projects should take account of fine-grained determination of landscape heterogeneity in all of the five aforementioned critical steps (Fig. 1). Mapping suitable sites at the individual-plant scale was hard to implement a few years ago due to high costs, low data precision, or both. However, current remote sensing technologies and products offer a resolution for decision-making process at the scale of meters or centimeters and at affordable costs. The many advances in microsite ecology arising from remote sensing (Zellweger et al. 2019) can be used, for example, to map wind-protected habitats for seedling establishment (Questad et al. 2014) or soil conditions and bedrock fractures that reduce water stress (Guirado et al. 2018). Ecological niche modeling can help to determine the suitable conditions for planting or sowing a particular species from the historical dynamics of satellite-derived high-resolution ecosystem functioning variables (Alcaraz-Segura et al. 2017; Arenas-Castro et al. 2019), such as land surface temperature (e.g. Bobrowski et al. 2018); canopy water content and photosynthetic activity (e.g. Vila-Viçosa et al. 2020); vegetation structure (Betbeder et al. 2017); or soil moisture, texture, and salinity (Kim et al. 2020). Finally, artificial intelligence, in particular deep learning, can boost these tasks through the exploitation of petabytes of remote sensing data, such as in the detection and counting of seedlings or adult crowns (Buters et al. 2019; Albuquerque et al. 2020), the identification of tree species (Egli & Höpke 2020), and the detection of scattered trees (Brandt et al. 2020; Guirado et al. 2021) that could serve for

postdisturbance regeneration. In summary, the fusion of remote sensing, ecological niche modeling, and artificial intelligence may help to identify the appropriate locations (e.g. microsite selection) and the appropriate time (e.g. by taking into account the historical and forecasted dynamics) for sowing or planting, thus adapting restoration to the fine-scale variation of environmental conditions (Cordell et al. 2017; Reif & Theel 2017).

Site selection cannot be dissociated from species selection, as the latter will impose the necessary requirements for each particular site, either at the landscape or microhabitat scale. In this sense, combining social, technical, and ecological knowledge and modeling of current species distributions and forecasted habitat suitability under future global change scenarios can be used to guide species selection (Gastón et al. 2014; Meli et al. 2014; Alcaraz-Segura et al. 2017). It is also important to consider that natural regeneration might be enough to guarantee forest recovery and at a lower cost (Chazdon & Guariguata 2016; Brancalion et al. 2019). Thus, a prior survey of the natural regeneration at the target site should be done, which can be conducted with field inventories and remote sensing. Artificial intelligence may further boost and enhance this task (e.g. Brandt et al. 2020; Guirado et al. 2021).

Step 2: Site Preparation

Proper preparation of the site for planting or seeding is critical for seedling establishment (Löf et al. 2016; Cardoso et al. 2020). Generally, the harsher the environment in regards to climatic and edaphic parameters, the greater the need for thorough soil preparation. One of the fundamental objectives of a PFR approach should be to reduce the impact of reforestation on the existing native community, which in many cases will be composed of early-successional species and may potentially have high biodiversity. In this sense, methods for soil preparation should be applied at plant scale, not extensively, and with the gentlest possible technologies which in addition try to take advantage of environmental clues that favor establishment (e.g. Fig. 2). The use of heavy machinery in particular should be restricted to sites where its impact is admissible, such as accessible sites with low slopes, set-aside lands, agroforestry systems, mining areas, and others. From a PFR perspective a first task should be to determine a priori the suitability of the soil at the meso (landscape features) and micro (individual plant) scales in order to choose appropriate sites and/or points in which seedlings or seeds should be placed, and to adapt soil to necessary preparations. Direct sampling of soil parameters prior to restoration would be a desirable measure, though it could rarely be done at a spatial scale large enough to map the selected sites. Remote sensing technologies may help to guide this task, for example, by using current and historical drivers such as topography, hydrological processes, soil moisture and temperature, primary production dynamics, or potential competition from herbaceous or invasive species (Reif & Theel 2017; Vaz et al. 2018; Reis et al. 2019) to select the best sites at both the landscape and microhabitat scale.

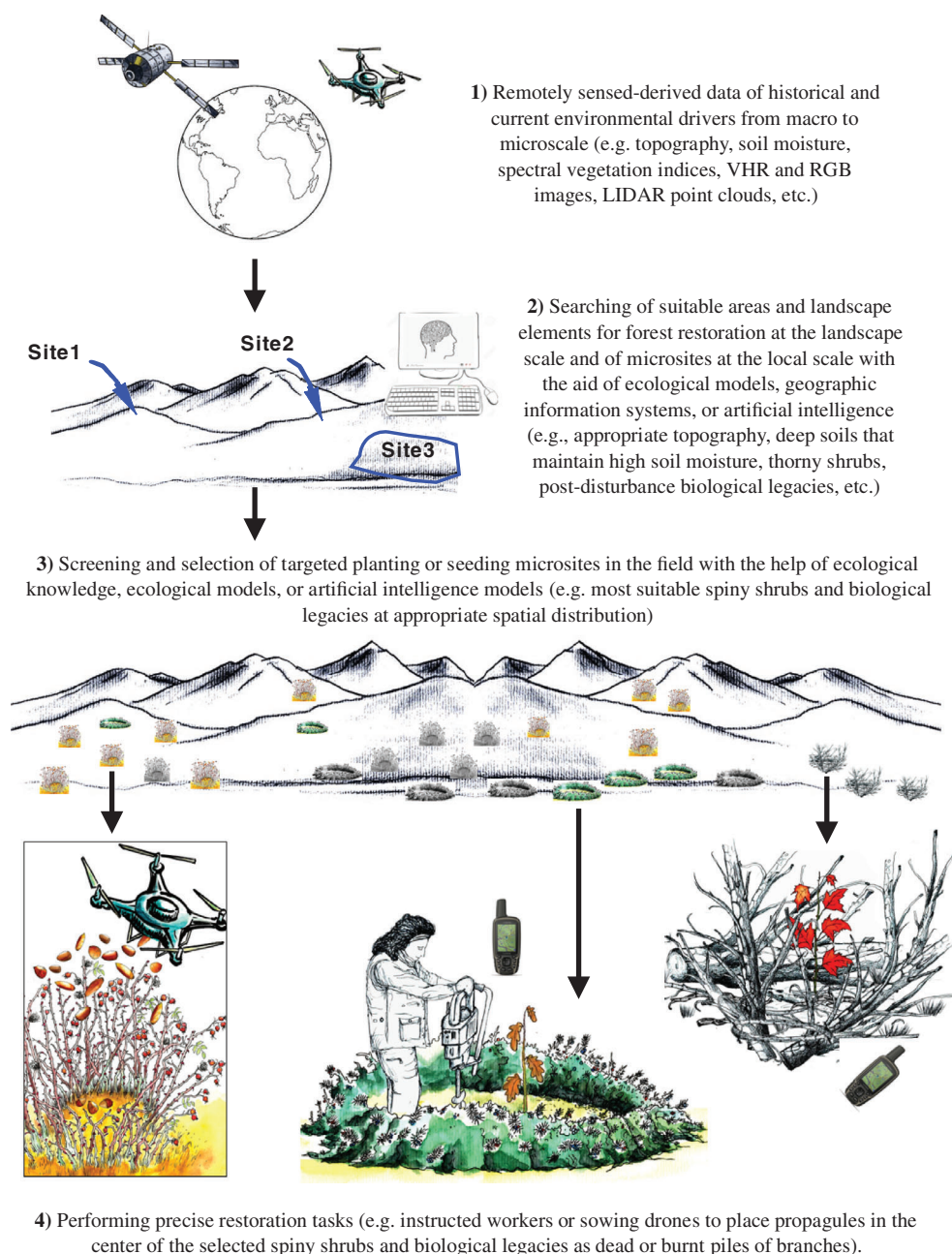


Figure 1. How remote sensing, modeling, and artificial intelligence may be combined for a precision restoration approach.

Step 3: Deciding Between Planting or Direct Seeding

Most forest restoration programs are based on the outplanting of seedlings previously produced in nurseries, whereas direct seeding is a minority activity (e.g. Jalonen et al. 2018). Seedling planting has the advantage of a higher survival rate, faster growth (at least in the initial stages), and to avoid seed predation (Palma & Laurance 2015; Leverkus et al. 2021b). However, the use of planting as a reforestation method may impair the development of the root system, particularly in species that produce a taproot. In such cases, it is common that this central, deep root cannot develop properly if the seedling is cultivated in a nursery,

suffering a number of deformities in comparison to naturally regenerated plants or plants obtained from direct seeding (Löf et al. 2019; Fig. 3A). This may produce a lower rooting depth and hence reduced water acquisition (Zadworny et al. 2014), which could reduce forest resistance and resilience to disturbances such as drought or pests. In addition, direct seeding reduces the impact of working operations, the risk of transferring plant diseases from nurseries to the field, as well as the costs in relation to outplanting (Palma & Laurance 2015; Raupp et al. 2020; see also Pérez et al. 2019 for shrubby species). Unfortunately, studies analyzing the long-term consequences of

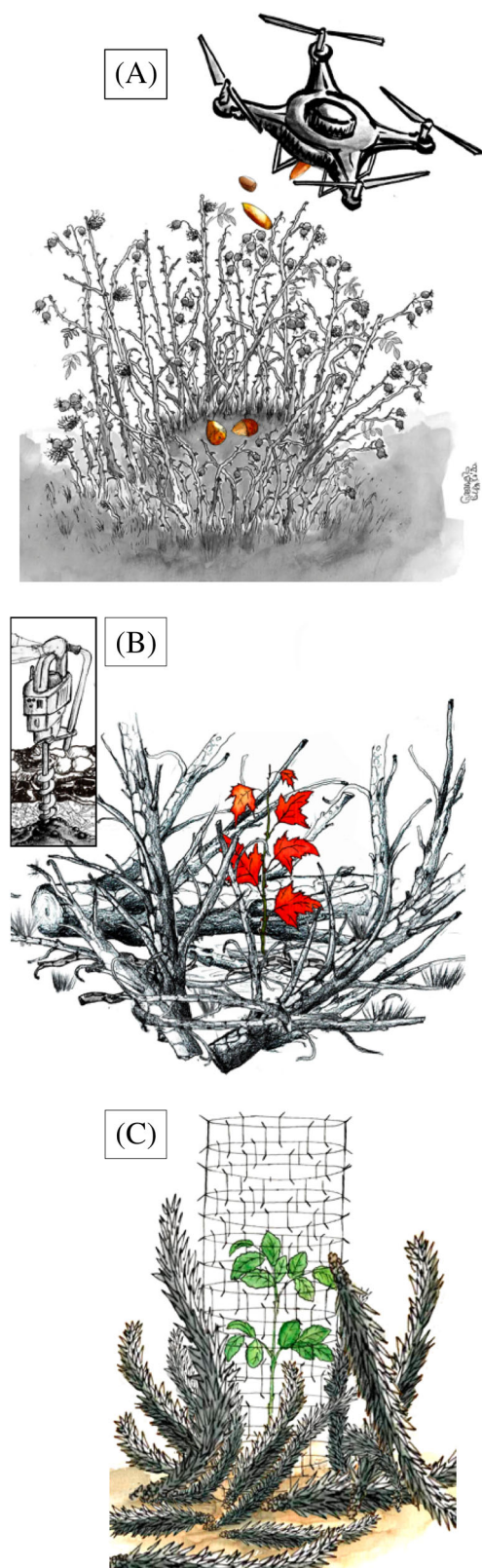


Figure 2. Examples of technologies and methodologies of interest for a PFR approach and how low-tech to high-tech and ecological knowledge can be combined. (A) Direct seeding can be implemented with the help of remote sensing and drones: microsites suitable for sowing can be located with high-resolution information derived from remotely sensed images, and the system can be further trained with the help of artificial intelligence to locate very specific spots (e.g. clumps of particular species that offer protection against herbivores). (B) Soil preparation can be accomplished with minimal disturbance (e.g. a small mechanical auger), selecting sites that maximize chances for seedling establishment. For example, direct seeding or planting can be done within remnants of biological legacies such as dead branches. This provides microclimatic amelioration, nutrient supply through decomposition, and protection against herbivores. (C) Protection of plants against herbivores can also be achieved with individual fences. Pictured is a patented device (protector “Cactus”) useful against large herbivores. Cut or dry branches can be added around the device to make the point less accessible (in this case, branches of *Araucaria*).

planting versus direct seeding for tree performance are virtually nonexistent (but see Zadworny et al. 2014). As a rule of thumb (although taken with caution due to the lack of studies), it is likely that the impact of planting versus direct seeding on the root system will increase with greater water stress in the restored site. In the same way, restoration success with direct seeding may increase in species with higher seed mass (Palma & Laurance 2015; Passaretti et al. 2020), a fact that may be motivated by a higher nutrient supply to the seedling or an increased likelihood that species producing large seeds also generate tap or deeper roots (Passaretti et al. 2020). In any case, the combination of remote sensing and highly precisely guided unmanned vehicles such as drones now offer the possibility of expanding the use of direct seeding to large areas and to places where outplanting would be very costly and even impractical (Fig. 2A), opening a new field of research and practice based in a PFR approach. The implementation of artificial intelligence in this process might further boost its applicability and efficiency (Fig. 1).

The use of direct seeding as a reforestation method may require the protection of seeds from seed predators (Löf et al. 2019). Strong efforts have been made in recent years to develop non-lethal and nontoxic methods at individual-seed scale to control seed predators, resulting in the development of several devices and the creation of several patents (e.g. Löf et al. 2019; Fig. 3A, inset). Protection against seed predators may also be achieved through the combination of different methodologies focused on different guilds of animals. For instance, the use of individual seed protectors against rodents can be coupled with the selection of sowing points below physical barriers, such as thorny shrubs or dead branches, for protection from larger animals (Leverkus et al. 2015; Fig. 2A). In summary, successful restoration via direct seeding is now feasible at large scales, and its combination with different technologies (seed protection, drone seeding, etc.) may substantially increase the precision and efficiency of forest restoration while reducing costs.

Step 4: Promoting Positive Ecological Interactions

Restore Key Plant–Animal Interactions That Drive Forest Recovery. There are ecological interactions that may foster forest recovery through secondary succession, and a precise

(Figure legend continued from previous column.)

sensing and drones: microsites suitable for sowing can be located with high-resolution information derived from remotely sensed images, and the system can be further trained with the help of artificial intelligence to locate very specific spots (e.g. clumps of particular species that offer protection against herbivores). (B) Soil preparation can be accomplished with minimal disturbance (e.g. a small mechanical auger), selecting sites that maximize chances for seedling establishment. For example, direct seeding or planting can be done within remnants of biological legacies such as dead branches. This provides microclimatic amelioration, nutrient supply through decomposition, and protection against herbivores. (C) Protection of plants against herbivores can also be achieved with individual fences. Pictured is a patented device (protector “Cactus”) useful against large herbivores. Cut or dry branches can be added around the device to make the point less accessible (in this case, branches of *Araucaria*).

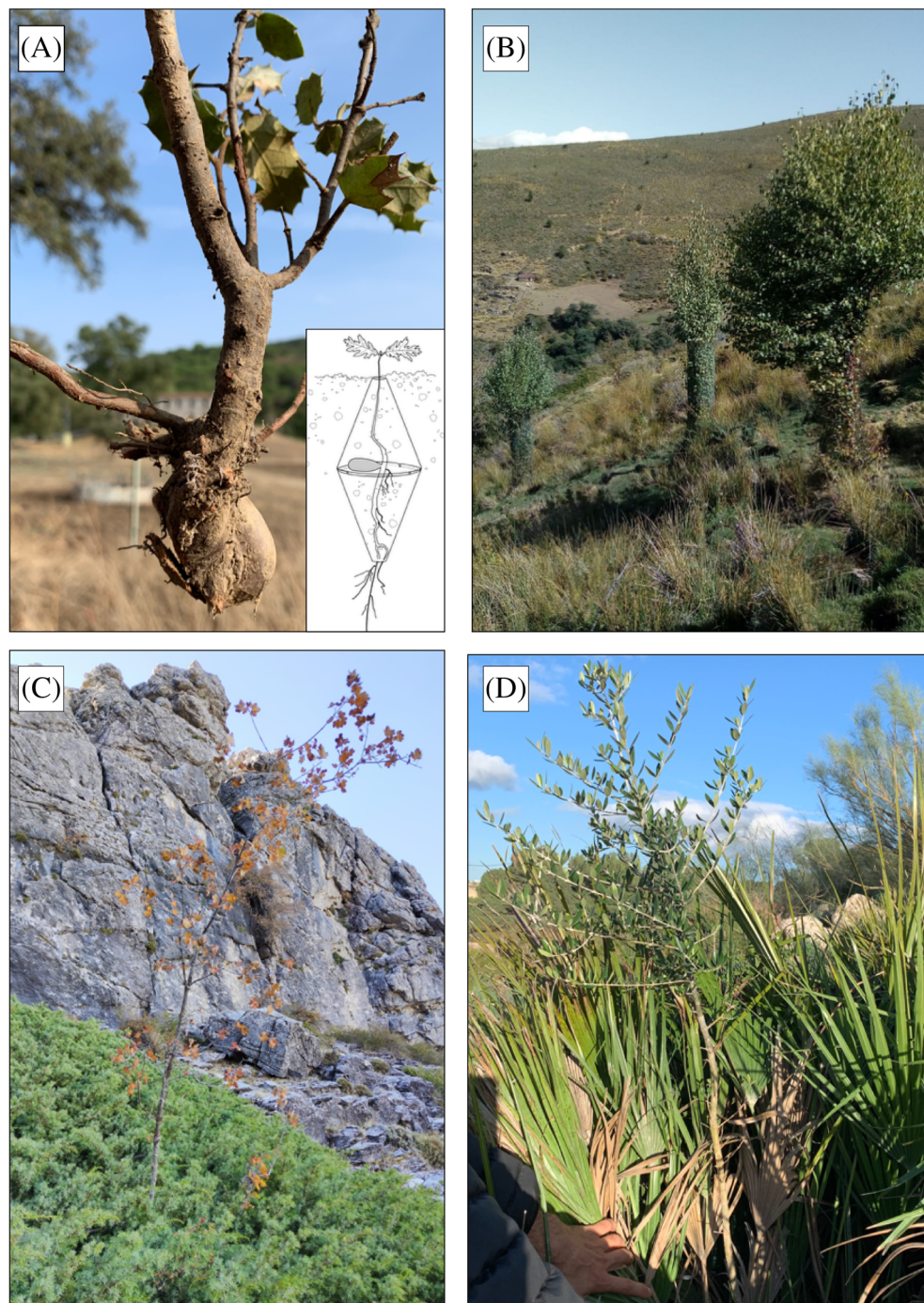


Figure 3. Some aspects that need to be considered for a successful restoration. (A) Cultivating seedlings in forestry containers may cause a deterioration of the root system after outplanting, particularly in the case of species that produce a taproot. Pictured is a Holm oak plant 3 years after transplantation, previously cultivated in 300 mL containers. Direct seeding may be a solution for the proper development of the taproot, but the seed may need protection against predators. In the inset, a seed shelter (a patented device) is used to protect the seed against rodents for direct seeding, providing conditions for a proper taproot development. (B) The creation of small nuclei of trees in suitable microsites and the maintenance of their protection until they reach a minimum size to be safe from most common environmental hazards may be more effective than widespread plantation. In the picture are a few trees recruited with 100% success in spots with higher soil moisture content and strong protection against herbivores with individual fences. Isolated trees in the background were also planted following a PFR approach. The distribution of trees currently allows for natural regeneration at the landscape level. (C) Natural recruitment of a maple (*Acer granatensis*), a highly palatable plant, within an individual juniper (*Juniperus communis*). This is a common pattern observed in the distribution area of the species, and might be emulated in restoration programs. (D) Natural recruitment of a wild olive tree within a palm (*Chamaerops humilis*), a plant that also offers protection against herbivores.

knowledge of the factors that determine them is necessary to boost restoration. For example, acorn dispersal by the Eurasian jay helps to restore native oak forests after fires. However, the jays do not cache acorns in the areas where postfire salvage logging (the removal of burnt trees, a common management practice after fires) is carried out, therefore blocking the positive effect of the bird (Castro et al. 2012). Thus, it might be more important to focus on the restoration or preservation of this interaction than to plan a widespread planting program.

Besides caring for the maintenance or recovery of the populations of the disperser, it is also necessary to have a minimum of scattered nuclei or individual trees in the landscape that act as seed sources. Therefore, another PFR approach could be to concentrate efforts in creating such nuclei or promoting those that remain in the landscape (Holl et al. 2019; Shaw et al. 2020), including fencing (protection against herbivores), pruning, fertilization, irrigation, elimination of weed competition, or any other action that can accelerate the growth of trees (Fig. 3B). Other approaches to foster seed dispersal could be the distribution of artificial perches or piles of branches to attract dispersers (Vogel et al. 2018; Castillo-Escrivà et al. 2019; La Mantia et al. 2019), the maximization of the presence of species that produce attractive fruits for seed dispersers early after planting and/or continuously throughout the year (De Almeida & Viani 2021), to increase the connectivity between nuclei (Lindell et al. 2013; Peña-Domene et al. 2016), offering seeds of interest to the dispersers in feeders (Silva et al. 2020), or even the reintroduction of the disperser (Genes et al. 2018; Mittelman et al. 2020). In summary, accounting for the role of seed dispersers and precise mapping of biological legacies (see Step 1) may be key for the success of forest restoration, so we need to know with precision the functioning of the system in order to plan proper measures.

Nurse-Based Restoration. The positive effects provided by nurse plants may be useful for forest restoration (Gómez-Aparicio 2009; Rey et al. 2009). The benefits of nurse plants for forest restoration basically come from two factors: reduction of environmental stress (mostly drought and radiation stress) and the reduction of herbivore damage (mostly browsing) (Gómez-Aparicio et al. 2008; Anthelme et al. 2014; Fig. 3C & 3D). In this sense, it is critical to determine the functional traits that boost positive interactions and minimize interference between the benefactor (nurse) and the beneficiary plants. Overall, life-form disparity, larger functional distances, or larger phylogenetic distances (parameters that may be highly interrelated) tend to increase the benefit provided by this approach (Gómez-Aparicio et al. 2004; Verdú et al. 2012; Navarro-Cano et al. 2019). In any case, the benefit of nurse-based reforestation may be determined by the management planned for the focal plants in the future. In cases where little care will be paid to the site after the reforestation, the use of nurse plants will be more important. If, however, we plan to take care of the restoration by applying some emergency irrigation, control of herbaceous competition, and others, the need for nurse plants may be reduced. In this sense, nurse-based restoration gains relevance with increased environmental constraints (the stress-gradient hypothesis), such as soil

degradation, water stress, or herbivore pressure (e.g. Gómez-Aparicio et al. 2004; Liu et al. 2013; Anthelme et al. 2014).

Fast growing trees can also be used as nurse plants to prompt the restoration of other target tree species in environments with strong competition from grasses, as in tropical and temperate ecosystems (Löf et al. 2014; De Almeida & Viani 2019). Nurse trees, when established with crown coverage, can reduce competing vegetation and simultaneously protect seedlings against late spring frost and improve stem form of slow-growing and often shade-tolerant target tree species (Pommerening & Murphy 2004; Löf et al. 2014). However, a few years after it has supported the early establishment of the target species, the nurse trees may compete strongly and thereby potentially harm the target species if not thinned or removed.

Another alternative is the use of nurse structures, for example, inert features or dead biological legacies such as stones, snags, or cut branches from pruning (Castillo-Escrivà et al. 2019; Oreja et al. 2020). Of particular relevance, both for its abundance at a global scale and its ease of management, is the use of dead wood after wildfires or insect outbreaks as a nurse structure (Fig. 2B). As they are not living items, dead logs and branches are not a source of competition, but improve the microclimate for the focal plants, provide nutrients through decomposition, and may reduce herbivory by acting as a physical barrier (Castro 2013; Marañón-Jiménez & Castro 2013; Marcolin et al. 2019; Fig. 2B). However, dead wood is usually removed in massive amounts from the site in postdisturbance management plans (Leverkus et al. 2021a). From the point of view of PFR, by contrast, this is a key element that provides clear advantages for seedling survival and recruitment.

Step 5: Postplanting Care

Protection Against Herbivores. Damage by herbivores (mostly insects, rodents, and large mammals) is one of the most important reasons for failure in the success of reforestation programs and natural forest regeneration (Anthelme et al. 2014; López-Sánchez et al. 2019; Garcia et al. 2020; Howe et al. 2020). Thus, to achieve success, control of the herbivore population or the protection of seedlings and saplings must be supplied at least until the moment they are large enough to withstand the presence of the herbivores.

Protection against large mammal herbivores (browsers) can be achieved through the use of nurse plants, as described earlier, which may act as physical barriers or chemical deterrents (based on the “associational resistance” or “associational refuges” concept; Callaway 2007; Stutz et al. 2015). Another alternative is the use of nurse structures or other biological legacies, such as dead branches (Fig. 2B). However, effective protection over time only occurs when the focal plant is completely surrounded by the nurse plant or structure, blocking access from the browser (García et al. 2000; Gómez et al. 2001). Thus, for effective restoration, it is necessary to ensure that the plant or seed is placed within a site that the herbivore cannot reach for years. This can be done by traditional manual procedures (reaching the inner part of the nurse plant or structure), but today this can also be achieved with high-tech approaches at microscale level, such

as the above-mentioned direct seeding with drones that spread the seeds inside clumps of branches, large thorny shrubs, or any other protective structure, which can be mapped at high precision with very high-resolution imagery (Figs. 1 & 2A). Protection from large mammals can also be obtained with artificial structures. As in the case of natural elements, maintenance of this protection must be ensured until the apical shoots of the plant are out of reach of the herbivores. Large fences (enclosing a significant portion of the territory) are a classic solution, though they are expensive and may impact other fauna and ecosystem functioning in general (Smith et al. 2020). The negative impact of fences is notably reduced in cases where they enclose reforested clusters of small size (e.g. fenced patches of a few hundred square meters distributed throughout the territory). Finally, individual fences are an effective solution that is costly on a per plant basis, but that can be concentrated in a much smaller number of seedlings or saplings (Fig. 3B). They can be built easily with iron or wooden pikes and wire mesh, and can also be acquired on the market (there are models patented; Fig. 2C). They have to be removed once the tree is safe from browsing, but a few dozen per hectare can be enough to start a functional forest. These fences have the additional advantage that they can be built with a mesh size that blocks access from small rodents, including those that excavate tunnels (e.g. voles and gophers) if they are inserted into the ground to certain depth.

Leaf-cutting ants are a major factor in forest restoration failure in the neotropical systems in particular (Garcia et al. 2020 and references therein). They have traditionally been controlled with insecticides and fungicides, but there are currently relevant advances in the use of more environmentally friendly methods such as those based on plant extracts or push-pull strategies (Della Lucia et al. 2020; Perri et al. 2021).

Artificial Watering. Water stress is one of the main causes of reforestation failure in large areas of the planet. Some of the measures mentioned above, such as appropriate site selection and preparation, the use of nurse plants, nurse structures, adequate root development, removal of herbaceous cover, and others, can reduce mortality by drought. However, if feasible, providing water to the seedlings during the first year of establishment will be the most straightforward way to increase plant survival and growth in environments with acute water limitations. The amount of water to be added will depend on the reforested species and the characteristics of the area (climate, soil type, etc.). Although there is very little information on the minimum thresholds that should be added, and the increase in survival that could be expected, the addition of an equivalent to approximately 20 to 50 L per m² of water during the dry season, evenly distributed in at least two periods, has repeatedly demonstrated to increase establishment success of different tree species in dry ecosystems (Mendoza et al. 2009; Siles et al. 2010). In certain cases, the irrigation could be applied using heavy machinery such as tractors with water tanks, for example in set-aside lands or agroforestry systems, or in general in any place where previous human intervention has created a system of gravel roads and other facilities that we can take advantage

of for restoration. This, in addition, may expand the area suitable for restoration at the landscape level, concentrating the planting points that will not receive water in landscape units with higher moisture availability and expanding the reforestation to sites where watering can be affordable.

Monitoring. Postplanting or seeding care may start from the very moment of site preparation, such as by providing protection against herbivores, adding hydrogels to retain water, etc. (Table 2), but it is a process that ideally requires monitoring through time. For example, the need for irrigation or protection from herbivores may be variable depending on the environmental conditions of the site and of each particular year. Moreover, as an undesirable side effect, site preparation or irrigation can result in an increase in herbaceous coverage (which will respond quickly to microsite improvement), so it can have an indirect negative effect by promoting competition (but see, e.g. St-Denis et al. 2018 for cases of a positive effect of the herbaceous cover). Those changes will also be variable and will require different postcare management strategies as the situation evolves. It is therefore preferable that plants be monitored as much as possible. This task is virtually impossible at a large scale without the implementation of novel technologies. Under a PFR perspective, a full set of remote sensing and artificial intelligence techniques can be used to monitor restoration performance and guide plant care in the pursuit of increasing success and effectiveness (Almeida et al. 2019; Camarretta et al. 2019; Reis et al. 2019). Should a problem be detected, more manual procedures at the precise location can be implemented, such as localized watering, weeding, or management of herbivore pressure (Fig. 1). This approach offers the additional positive effect of generating the required conditions to implement adaptive management (Camarretta et al. 2019).

Conclusions

The classic reforestation approach has largely considered planting to be the final step of forest restoration processes. We suggest that to restore large areas of forests globally we need to facilitate the growth of resilient adult trees into the near future, with an ecological and landscape structure that allows for the functioning of further natural succession. There is no sense in planting trees or sowing seeds if we do not protect the plants from the hazards that they will face from the very moment that they are placed in the field, and which will persist for years or decades. In this sense, our call for a PFR approach would help to increase restoration efficiency, as it puts the focus on increasing the success of each particular plant once they are in the field while minimizing costs and negative side effects. PFR can be seen as a logical consequence of the development of techniques and methodologies to which the ecological restoration and nature conservation sector has recently gained access, together with the guidance of the deep knowledge of the ecological processes that operate in forest communities.

In summary, we advocate for a PFR approach to restore forests. This may imply greater initial costs per plant, but ultimately

will be more efficient in both ecological and economical terms if we substantially increase the probability of getting adult (reproductive) trees in the future with the appropriate landscape distribution to promote succession. For that, it might be better to ensure the establishment a few dozen trees per hectare instead of planting hundreds of them with uncertain futures. There is currently great social and political momentum to restore forests, but the chances for failure are immense if precise care of the trees is not taken. If this were to happen, we would lose a great social, emotional, and ecological opportunity. Efforts to ensure the success of forest restoration are now more of a priority than ever.

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