CHAPTER 6

Forward-looking practices for climate-responsive site preparation, direct seeding, and planting

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Introduction

The successful establishment and early growth of tree seedlings are critical in shaping the future structure, vitality, and function of forests. These initial stages lay the foundation for the ability of forests to provide multiple benefits, including timber production, carbon sequestration, biodiversity conservation, and recreational opportunities. Regeneration strategies must account for a range of environmental and site-specific factors, including soil conditions and the legacy of past land use. Whether new forests are being established on an area devoid of earlier forest cover, e.g., former agricultural land (afforestation), on degraded sites, or on forest lands after harvesting or disturbances (reforestation or restoration), past land use significantly affects the choice of regeneration methods. Moreover, practical considerations such as regulatory frameworks, the availability of forest reproductive material, and workforce capacity further shape decision-making. Ensuring that newly established forests align with local ecological, economic, and societal needs requires a context-sensitive approach that balances long-term sustainability with operational realities.

Forest establishment can be achieved through active methods, such as planting or direct seeding, or passive approaches that rely on natural regeneration. These methods can be enhanced through targeted interventions, including soil preparation and fencing. Each method presents unique advantages and challenges, particularly in the context of increasing climate change resilience (see Chapter 3 for further details). Traditionally, regeneration and site preparation decisions have been guided by factors such as management objectives, forestry regulations, site-specific adaptation needs, cost-effectiveness, and local preferences. These factors, together with biodiversity conservation, land use history, and ecosystem

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service provisioning, including carbon sequestration, remain central considerations (Busch et al., 2024). However, as climate change intensifies, greater emphasis is needed on understanding how regeneration choices influence forest resilience and how both traditional and innovative tools can support adaptive forest establishment.

Adapting to new environmental conditions necessitates a critical reevaluation of traditional practices and knowledge, as well as the practical potential of forward-looking alternatives. In recent years, innovative methods and strategies have emerged to improve the success of forest regeneration efforts. These include the use of introduced species and promising or documented better provenances and other selected genetic materials (see Chapters 4 and 5) that may be better adapted to changing climatic conditions, as well as improved planting and seeding methods that increase survival rates. In addition, the incorporation of ecological principles—such as the promotion of beneficial biodiversity and soil health—can significantly contribute to more sustainable outcomes and is therefore increasingly being incorporated into forest regeneration. By using a combination of traditional and novel approaches, forest managers can implement adaptive strategies that respond to changing environmental pressures and support the long-term management objectives, health, and productivity of forest ecosystems.

This chapter examines various regeneration situations, techniques, and site preparation methods, highlighting some available and emerging innovations that can promote sustainable pathways to enhance establishment success. Our approach follows the sequence in which reforestation or restoration decisions are typically made, recognizing that site conditions can range from bare ground previously used for pasture or abandoned farmland to a clearcut forest, land after a shelterwood harvest, or other disturbed or degraded land requiring restoration. The choice of regeneration method—active or passive, direct seeding, or planting—is often determined by site conditions, cost, the availability of species and stock type, or a combination of these factors. The goal of site preparation is to produce as close to optimal growing conditions as possible for young plants, both above- and belowground. The choice of necessary site preparation depends on these factors. We introduce innovative approaches for assessing and improving site conditions and supporting seedling establishment, including precision seeding and facilitation of beneficial microbiomes in planting sites. Drawing on scientific literature and experience, this chapter seeks to equip practitioners with up-to-date knowledge to support informed and forward-looking decisions on planting and site preparation practices.

Adapting the regeneration methods to the site conditions and management objectives

Stand-level conditions—silvicultural systems and former land use

Silvicultural systems integrate all silvicultural measures that drive the development of the stand towards the management targets (Matthews, 1991; Bottalico et al., 2014). Two main categories can be separated: high forest and coppice forest systems (Table 6.1). Implementation of a silvicultural system affects the structure and composition of the stand and indirectly causes changes in ecological conditions, thus determining a suitable regeneration approach. In current forestry practice, different variants of silvicultural systems are adapted to local or regional conditions (Fig. 6.1). Because climate change will cause significant changes in these conditions, it may be necessary to reassess the suitability of different systems.

Across the different silvicultural systems, conditions such as former land use, presence or absence of an overstory, soil conditions, and competing vegetation influence the choice of site preparation techniques and the feasibility of natural versus artificial regeneration (Table 6.2). Afforestation on degraded sites and postdisturbance regeneration, such as after salvage logging, present unique challenges that influence site preparation and regeneration choices. Soil degradation, compaction, loss of organic matter, and competition from invasive vegetation often limit natural regeneration success. In cases where noncommercial stems remain after disturbance, they can either facilitate regeneration by providing microhabitats or hinder it by competing for resources. On heavily degraded sites, restoration efforts often require intensive interventions, including deep soil preparation, fertilization, and selective planting of resilient species. Similarly, in post-disturbance scenarios where salvage logging has removed commercial timber but left residual vegetation, managing competing species and maintaining soil stability are key considerations. Whether using passive (natural regeneration) or active (planting/seeding) methods, adapting site preparation to these challenges is crucial for ensuring forest establishment success.

The presence or absence of an overstory, which includes both trees and understory vegetation, is a critical factor shaping the conditions for seedling establishment. Overstory cover influences seedling growth through resource competition and microclimate regulation. On the one hand, a dense overstory limits light availability, suppressing the growth of shade-intolerant species and intensifying competition for water and nutrients, particularly in drought-prone or nutrient-poor soils (Pérez-Devesa et al., 2008; Rautio et al., 2023). On the other hand, they can also serve as nurse trees or seed trees when properly managed. Some overstory species also release allelopathic compounds that inhibit seedling development (Fernandez et al., 2008; Cummings et al., 2012). Additionally, the overstory can stabilize site conditions by increasing local humidity, reducing temperature extremes, and minimizing soil evaporation, which is particularly beneficial in semi-arid environments. The trade-offs among these effects must therefore be carefully weighed in site preparation. In shaded environments, selective thinning can enhance light penetration while preserving moisture-retaining canopy functions, whereas on exposed sites, maintaining partial overstory cover can buffer seedlings against environmental stressors.

Table 6.1 Basic characteristics and objectives of different silvicultural systems.

Silvicultural system		Conditions for regeneration	Target stand condition
High forest system	Clearcutting system	The parent stand is removed with one cut.	Even-aged structure
	Uniform shelterwood system	Opening of the canopy gradually and uniformly throughout the stand.	Even-aged and uniform structure
	Group system	Opening the canopy gradually in properly arranged groups.	Even-aged structure
	Strip shelterwood system	Openings of the canopy gradually in the form of stripes, groups, or wedges.	Even-aged or uneven-aged structure
	Irregular shelterwood system	Opening of the canopy gradually, in irregularly scattered groups.	Uneven-aged structure
	Single tree selection system	Removal of individual trees continuously on the entire surface.	Uneven-aged structure
	Group selection system	Removal of individual trees continuously on scattered groups.	Uneven-aged structure
	Two-storied high forest system	Regeneration under complete protection of the parent stand.	Even-aged structure
	High forests with reserves	Regeneration under the protection of individual reserve trees of the parent stand.	Uneven-aged structure
Coppice system	Simple coppice system	The parent coppice stand is removed by clearcutting.	Even-aged and uniform structure
	Coppice with standards	Establishing high-quality individual trees of various ages, while in the understory there is an even-aged coppice forest as a base.	Uneven-aged structure
	Selection coppice system	Removal of individual trees continuously on the entire surface.	Uneven-aged structure
	Conversion	Conversion of stand origin by natural regeneration or planting.	Even-aged or uneven-aged structure

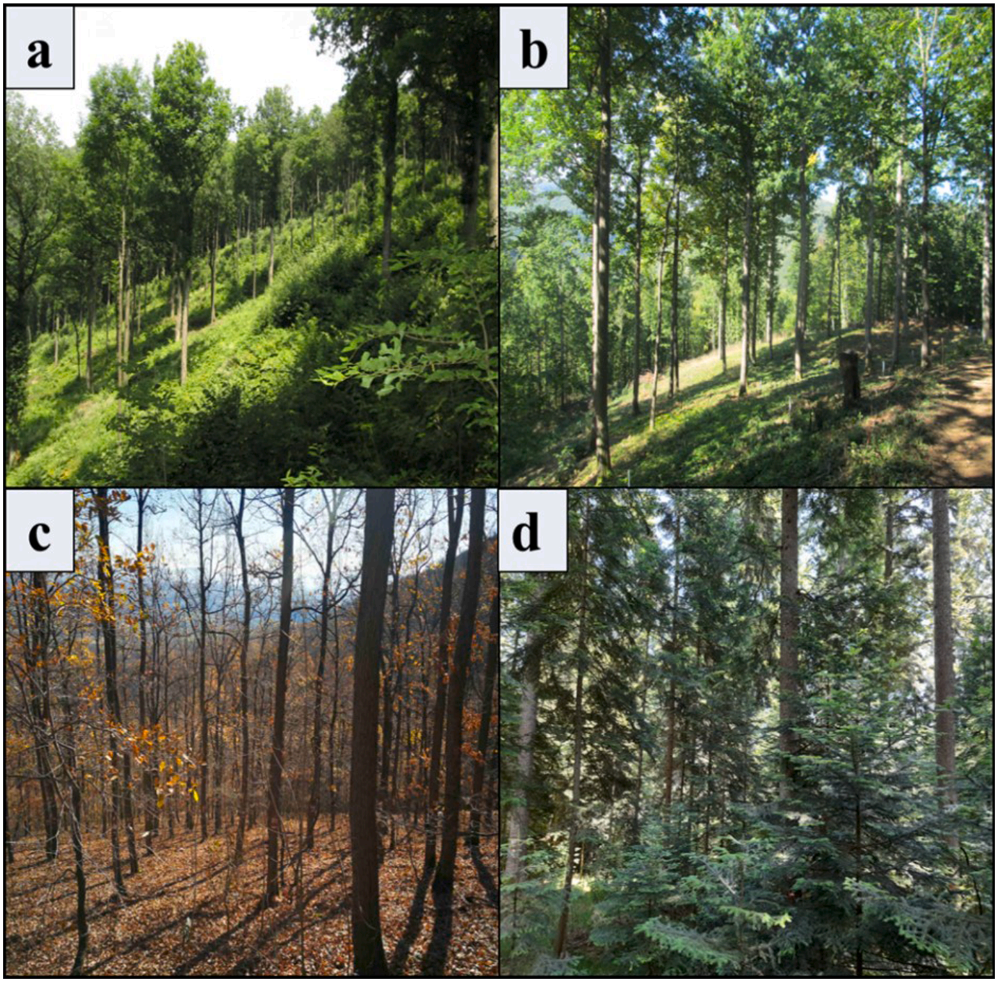

Figure 6.1 Different silvicultural systems in practice: (a) uniform shelterwood; (b) irregular shelterwood; (c) simple coppice; (d) single tree selection. *(Credit: Branko Kanjevac.)*

Clearcutting removes the overstory entirely, maximizing light availability but increasing risks of soil desiccation, erosion, and temperature extremes. It often promotes intense competition from grasses, herbs, broadleaves, and shrubs, requiring additional site preparation and vegetation control (Raymond and Bédard, 2017). Shelterwood systems, which retain a partial overstory, balance light access with microclimate stabilization, benefiting species that gain competitiveness and protection from moderate shade during early development. Selection systems, in which individual trees or small groups are selectively removed, maintain continuous canopy cover and promote biodiversity of shaded habitats, but require careful management to avoid excessive competition.

Table 6.2 Matrix of conditions and limitations to regeneration activities across the former land use types.

Former land use	Typical examples of conditions	Possible limitations to regeneration
Forest land use	Clear-cut	Slash, stumps, dry and hot, pests
	Shelterwood	Light and moisture competition, pathogens
	Degraded (structure, species composition, disturbance regime, or a combination)	Lack of desired species, light, and moisture competition, competing vegetation
	Wind disturbed	Salvage logged, deadwood, clearcut soil conditions
	Fire suppression	High fuel loads, ladder fuels
	Wildfire	Salvage logged, low fertility, exposed soil
	Invasive soil pests or pathogens	Lack of resistant species, dysbiosis (imbalance) of soil microbiome
	Altered inundation regime	Waterlogged or dry, lack of desired species sources
Nonforest land use	Pasture	Low fertility, competing vegetation, compacted soil
	Row crop agriculture	Competing vegetation (if long abandoned) Residual fertility
Degraded land	Mined land	Infertility, compaction, instability, lack of appropriate microbiota, toxic substances
	Eroded soils	Infertility, dense soil, lack of appropriate microbiota
	Saline soil	High salinity, crust

Harvested forest sites often contain logging residues, stumps, and roots that may impede planting, necessitating further site preparation. Coppicing can exacerbate climate change effects on forest biodiversity by altering microclimates and understory vegetation and reducing the temperature buffering capacity of the forest (Santi et al., 2024). Thus, coppicing systems should be implemented cautiously, especially in Mediterranean regions, where heatwaves and droughts are expected to be more frequent and intensive.

All management interventions influence the forest environment and habitats, and biodiversity will change to some extent. Leaving forests unmanaged is very much a question of the time scale involved in evaluations and goal settings. Maintaining variation in the forest environment and habitats on a long-term basis can be an active strategy (Schall et al., 2018).

From stand-oriented to tree-oriented management—regeneration under nurse trees

Adaptation of forest management to new challenges and circumstances brought by the modern age requires the continuous harmonization of existing methods and the development of new ones to mitigate critical problems in forestry. Considering these challenges and climate change, the shift from stand-oriented silviculture to tree-oriented silviculture becomes increasingly logical (Abetz and Klädtke, 2002; Spiecker et al., 2009; Manetti et al., 2016). The concept of *nurse trees* reflects this shift (Fig. 6.2). In the context of climate change, nurse trees or nurse crops can provide a sheltered forest environment in the absence of shelterwood trees of the former stand. This may be because of poor stability or simply loss of the former stand (windthrow, insects, and diseases), and nurse trees are an alternative in the regeneration process that helps to reduce the negative effects of abiotic stresses. They do this by regulating microclimatic conditions, mitigating the effects of extreme climatic events, and reducing the impact of drought stress in seedlings (Caldeira et al., 2014; Andivia et al., 2018). The sheltering effect of nurse trees can also mitigate the negative effects of biotic factors (Bertness and Callaway, 1994).

In general, nurse trees or nurse crops are established as part of the regeneration method used to provide the same functions for regeneration of the main or crop species as performed by shelterwoods or shelter trees (Figs. 1 and 2). Shelterwoods or shelter trees belong to the mature or existing stand under regeneration, whereas nurse trees or nurse crops are established as part of the regeneration method. Where nurse trees

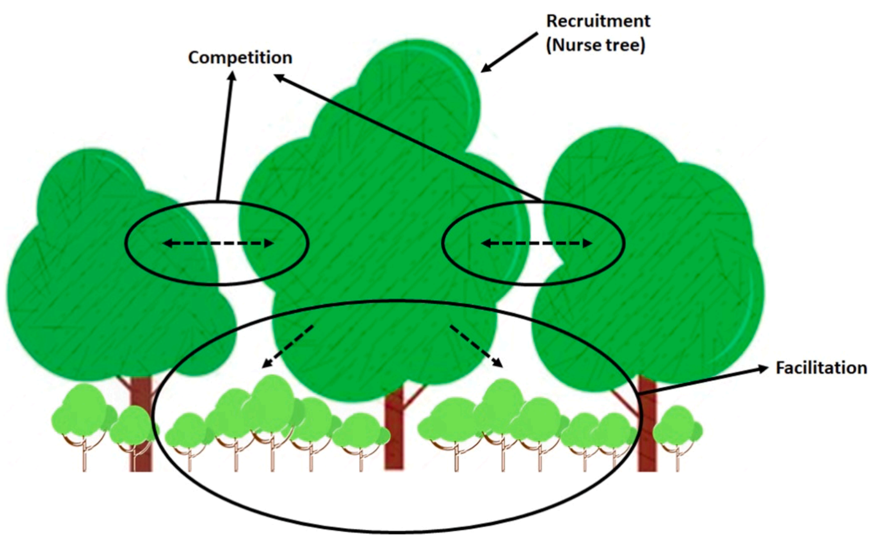

Figure 6.2 The concept of shelterwood. *(Credit: Branko Kanjevac.)*

are available and feasible, they perform beneficial functions that the mature or existing stand cannot provide reasonably (see the section on facilitation).

Forest regeneration methods that involve gradual removal of the parent stand implement the concept of shelterwood. After silvicultural operations, the remaining trees function as shelter by supporting balanced development of seedlings and producing additional seeds necessary for regeneration. In mixed forests, the remaining trees can enhance the survival and growth of seedlings by ameliorating the harsh microclimate that can occur in open conditions. Such microclimates are often characterized by elevated levels of light, extreme temperature fluctuations, and water deficits (Childs and Flint, 1987). Shelterwood provides wind protection, lowers water levels in poorly drained habitats, and N-fixing tree species can provide additional nitrogen (Landhäusser et al., 2003; Kelty, 2006; Löf et al., 2014). The use of nurse trees in mixed plantations provides a short-term advantage in building forest structure and increasing productivity, which can be directly reflected in future strategies and the success of regeneration (Löf et al., 2014). Nurse trees can also provide fast growth and increased CO_2 sequestration in the early and otherwise less productive phases of regeneration. Thus, nurse trees are an invaluable tool for establishing forests with sensitive tree species and for ecosystem recovery after disturbances (Bauhus et al., 2017).

Although sheltering effects in silvicultural practice offer numerous benefits, it is crucial to consider species compatibility within the stand. For instance, shrub vegetation in various parts of Europe can have varying impacts on reforestation. In central and northern Europe, a combination of dense vegetation and, in most cases, relatively mild drought stress makes existing shrub vegetation a source of competition for nutrients and light. Therefore, regeneration is often more successful after removing this vegetation or by planting in areas that avoid the shrubs (Savill et al., 1997). On the other hand, in the southern parts of Europe, where dry summers and extremely high temperatures are a major problem, shrubby vegetation can be used as nurse plants (García et al., 2000; Gómez et al., 2011). Plantations of nonnative tree species may have a detrimental impact on the environment, but they can also have a protective function and a nurse tree effect in the process of restoring natural forests (Feyera et al., 2002). It should be considered that the nurse tree or nurse crop concepts need intensive monitoring and management interventions. Nurse trees can be managed similarly to shelterwood by removing the nurse trees and releasing the target species (Fig. 6.3); this works well using fast-growing species such as *Populus* spp. as the nurse tree (Löf et al., 2014; Nord-Larsen and Meilby, 2016).

Regeneration techniques

The choice of forest regeneration approach should consider site-specific conditions, long-term goals of forest management, and resource availability. Natural, or passive, regeneration relies on the natural dispersal and germination of seeds and sprouting of residual stumps and roots, often resulting in lower initial costs and the preservation of local genetic diversity and ecological integrity (Williams et al., 2024). However, it depends heavily on favorable environmental conditions, availability of vital seeds, and the absence of excessive competition or disturbances (Löf et al., 2019). Natural regeneration implies that the species and genetic material considered adequate for the future climatic conditions and management objectives are already present at the site, and this can be successfully regenerated to form the future forest; however, this is not always the case. For instance, Norway spruce can regenerate in locations where it will later (e.g., after 30 years, as moisture demands increase) fall victim to drought and ultimately die. Artificial regeneration methods, including active planting and direct seeding, offer greater control over the regeneration outcomes (Palma and Laurance, 2015). They enable the introduction of genetically improved stock with enhanced growth, pest and disease resistance, or climate adaptability, making them prioritized alternatives when the goal is to achieve specific management objectives, such as climate-resilient stands.

In practice, the different regeneration efforts often represent a gradient between the active and passive means (see Chazdon et al., 2024). Interventions such as site preparation, including soil scarification during mast years for oak or beech, can significantly enhance the outcomes of natural regeneration, blurring the lines between passive and active approaches. Instead, artificial regeneration may utilize natural regeneration, blending deliberate intervention with ecological spontaneity. For instance, gaps between planted clusters may be filled naturally, for example, in cluster planting (Saha et al., 2016) or applied nucleation (Holl et al., 2020).

Figure 6.3 An example of a nurse crop. Poplar and black alder were planted 11 years earlier, and in the same year, the beech were sown on agricultural land as an afforestation project. *(Credit: Palle Madsen.)*

Planting

The use of nursery-grown planting stock provides many advantages for climate change-adapted forestation. Seedlings can be outplanted when environmental conditions are optimal, when seedlings have reached a developmental stage that facilitates their survival after planting in the field. Other advantages include better control of environmental factors during the germination and early growth stages, extension of the planting season, and easier application in the nursery than in the field of effective predator, weed, and disease control measures. Production costs for container seedlings can be high due to costs for material (greenhouse space and facilities, growing medium, water and nutrients, containers, electricity, etc.), labor, and transportation (depending on the distance from the nursery to the planting site). However, on planting sites characterized by harsh environmental conditions, such as low water availability that inhibits seed germination and seedling establishment, planting high-quality 'drought-resistant' seedlings may be the best option despite the higher initial costs (Tsedensodnom et al., 2022).

By aligning seedling characteristics with site conditions, forestry practitioners can improve establishment success and reduce mortality (Chapters 4 and 5). Rather than a 'one-size-fits-all' approach, successful forestation is guided by the target seedling concept, which emphasizes matching the physiological characteristics of the seedling to the specific demands of the site, providing a framework for linking stock type and site preparation (Dumroese et al., 2016). A target seedling possesses specific morphological and physiological traits suited to the planting site's conditions. For example, seedlings intended for dry or nutrient-poor sites may be grown with larger root systems or preconditioned for stress tolerance, ensuring better survival and growth postplanting. Preconditioning techniques, such as drought tolerance conditioning (Puértolas et al., 2024), seed treatments for disease resistance (Villalobos et al., 2023), and the application of beneficial mycorrhizae (Birhane et al., 2023), can further enhance the ability of seedlings to withstand site-specific challenges.

Matching the seedlings and site

To create optimal conditions for tree seedlings, it is essential to consider how their needs can be met by the site and supported by forestation practices (for details of species choice and seedling quality, see Chapters 4 and 5). The key is to understand how the above- and belowground portions of the seedlings respond to site properties. Plant root systems are particularly important for site preparation decisions.

Planted seedlings need to rapidly secure the uptake of nutrients and water through the roots and tolerate environmental and biological stress. Of crucial importance is the architecture of the root system, because it enables water and nutrient uptake and anchors the plant to the soil, controlling the postplanting survival and growth of seedlings by enabling efficient extraction of water and nutrients that are heterogeneously distributed in the soil (Chiatante et al., 2003; Davis and Jacobs, 2005; York et al., 2013; Dumroese et al., 2019). Another important attribute of roots affecting field performance is root length, which is particularly important at planting sites with limited water availability or on steep slopes, where longer lateral roots in deeper soil horizons ensure better water and nutrient uptake (Nyam-Osor et al., 2021; Montagnoli et al., 2022; Del Campo et al., 2007), and a strong taproot provides mechanical stability to the trees (Dumroese et al., 2019; Chiatante et al., 2021).

The stock types differ in their root system structure and therefore require different site preparation practices. Direct seeding produces seedlings with a root system that is morphologically like those obtained through natural regeneration under the same environmental conditions (Leskovar and Cantliffe, 1993; Ammer and Mosandl, 2007). Bareroot seedlings with their exposed roots often require intensive site preparation that loosens the soil, along with careful timing of planting to minimize desiccation risks. With their intact root plugs, container seedlings are more adaptable to a range of conditions and can be planted later in the season, allowing greater flexibility in planting activities. In the case of nursery-grown stock, factors such as container shape and size (i.e., volume) or type of soil preparation require attention for their potential effect on root growth and development. For example, a container that is too small can cause root deformation, or inadequate site preparation for planting bareroot stock affects the normal root growth and development, leading to compromised seedling performance in the field (Pinto et al., 2011; Ivetić and Škorić, 2013). Container designs that effectively provide air pruning while the seedling develops in the nursery are highly recommended to allow for the development of symmetric root systems in containers that are prepared to expand into the planting bed quickly after planting (Chapters 4 and 5). The taproot of ‘plug plus’ stock is generally well developed in diameter and the number of lateral roots, and their root architecture is like that developed by seedlings growing in bareroot beds or seedlings obtained by direct seeding in the field.

Roots of seedlings can be significantly affected during harvesting, storage, handling, and shipping operations. Rapid decrease in plant quality due to dehydration of fine roots between harvesting and planting has been described (Chiatante et al., 2002, 2003). Exposure to extreme temperatures (e.g., heat or freezing) during handling and shipping can have negative effects on roots. Therefore, it is necessary to train the personnel responsible for planting activities to avoid mechanical damage to roots through careless handling.

Advances in planting

Remote sensing tools for site inventory

Remote sensing and digital technologies are increasingly important tools in climate-smart forestry, driven by the increasing rate of environmental change that makes available information quickly outdated and no longer relevant in decision-making (Fassnacht et al., 2023). Digitalization of forestry activities provides access to timely and accurate information that allows fine-tuning management decisions to changed site conditions. Digitalization also provides new opportunities for near-real-time monitoring of artificial regeneration efforts. However, while digital technologies can transform forestation practices, the current possibilities of practitioners to use them vary greatly, depending on social and economic conditions (Urzedo et al., 2023).

Precision forestry uses data collected by several types of sensors and platforms—from satellites to mobile phones—combined with artificial intelligence to provide guidance for informed decisions. Drones equipped with sensors (e.g., multispectral video cameras and LiDAR) have become affordable (Stanturf et al., 2024) and can be useful tools for collecting preplanting information from the regeneration site.

Based on laser data, high-resolution maps showing near real-time data on site conditions, such as soil moisture, can be retrieved online. For instance, in Sweden, the SLU Soil Moisture Map (http://bit.ly/4fJzepo) combines information from 24 different maps with field data from 20,000 sample plots from the Swedish National Forest Inventory, distributed across Sweden, to train the model (through machine learning) on soil moisture content. This ensures that the map is tailored to different regions with varying topography, climate, and soil types. The scalable map shows the likelihood that a pixel on the map will be classified as wet.

Drone-assisted counting of planting spots

Estimating the number of mounds created at each site is a critical step in planning planting operations, and errors in it affect the logistics of planting, leading to time and cost inefficiencies. Traditionally, counting has been done by multiple workers who visually tally the number of mounds in specific areas and then extrapolate the results to the entire regeneration area. Recently, the use of drones has been used to capture aerial imagery, which is then manually analyzed to visually count planting microsites by operators. To eliminate human mistakes during mound identification and the often-invalid assumption of constant mound density, artificial intelligence (deep learning) models have been developed (Zgaren et al., 2023). Drones can also be used as fleets (swarms), equipped with identical or different sensors, to allow rapid and comprehensive data collection from the regeneration area (Tahir et al., 2019).

Mobile phone apps for site information

Mobile phone apps can provide user-friendly, low-cost tools for practitioners to receive and collect data regarding seed and seedling availability and site properties (e.g., vegetation structure and canopy openness). However, many of them need more development to provide optimal support for preplanting decisions or monitoring of the success of regeneration efforts (Schweizer et al., 2024).

Digital twins for interactive simulations

In the future, regeneration practices may also be assisted by a digital twin approach, i.e., a computer-generated equivalent of the actual physical world that can simulate physical objects, physical states, and processes. A digital twin integrates spatiotemporal data, 3D visualization, and an intelligent interactive environment with forest management theory, allowing interactive simulation of the outcomes of different silvicultural practices (Qiu et al., 2023). This approach could be implemented to better understand microsite conditions. Microlevel information is particularly important, as the success of seedling establishment and early growth largely depends on microsite conditions, e.g., availability of water and nutrients in the proximity of seedlings (Nordin, 2023). This detailed information is needed for autonomous planting machines (Hansson et al., 2024).

Promoting beneficial microbiome in seedlings and soil

The importance of plant-associated and soil microbes for seedling growth and health is increasingly acknowledged, and the ability of plants to host beneficial microbes is receiving increasing attention. The concept of the *holobiont* refers to a paradigm shift in understanding the functions of plants that, together with their associated microorganisms, are now considered as a functional biological entity (Vandenkoornhuyse et al., 2015). Breeding strategies that utilize this concept, where microbes are one of the targets of the selection process, are creating a range of better-adapted seedlings without changing plant genomic information (Wei and Jousset, 2017; Marco et al., 2022).

The absence of beneficial soil microbes can significantly reduce the success of plant establishment and early growth, and enhancing the presence of key microbial symbionts is therefore emerging as a potential practical measure facilitating sustainable forest regeneration. The role of mycorrhizae in plant nutrition and water status is well established (Usman et al., 2021), but also other microbes (e.g., endophytes) may be important for disease control (Doty et al., 2023). While efforts have focused primarily on belowground microbiota (mainly mycorrhizae), the aboveground microbiome—found in the leaves or needles—is increasingly investigated as a potential factor in plant health (Busby et al., 2022). A study conducted in a postmining landscape in Estonia showed that regeneration of species-rich vegetation by introducing native arbuscular mycorrhizal fungi from soil was improved (Vahter et al., 2020), demonstrating the field applicability of the approach. Moving healthy forest soil and the associated microbes in it from one location to another (soil transplants) is a low-tech method for supporting development of beneficial microbial communities on the site and promoting restoration of disturbed ecosystems and plant community development (Wubs et al., 2016). Studies have also shown that plants amended with either mycorrhizal fungi or whole soil grow more biomass and attain greater height (Koziol et al., 2021).

Direct seeding

Direct seeding is the practice of dispersing seeds directly into an area for forest regeneration purposes. Although it may be considered favorable because it can be applied quickly over large areas and on inaccessible sites, the method fell out of favor due to its unpredictability (Palma and Laurance, 2015; Oliet and Jacobs, 2012). Nurseries gained importance for forestation, especially for reforestation of commercial species, due to improved success and because high-quality seed and advanced genetic material are limited resources and expensive. The global demand for forest regeneration is growing, resulting in large-scale tree planting initiatives that cannot be accomplished solely by planting stock from nurseries (Fischer et al., 2016). Thus, direct seeding is gaining renewed interest for its scalability and cost-effectiveness (Grossnickle and Ivetić, 2017; Pedrini and Dixon, 2020). In the earliest phase of forest regeneration, when seeds germinate and seedlings begin development, plants are extremely sensitive and vulnerable. In natural ecosystems, this vulnerability is compensated for by repeatedly dispersing enormous amounts of seed over the years, allowing for considerable losses. Recent advances in direct seeding have been aimed at addressing challenges such as low germination rates and seed predation, making it a more dependable and widely applicable method for forest regeneration (Palma and Laurance, 2015; Grossnickle and Ivetić, 2017).

Technological innovations, particularly in the fields of automation and precision seeding, enable large-scale seed dispersal in previously inaccessible or degraded areas (Castro et al., 2024). Advances in seed (pre)treatment techniques—such as seed coating, biochar infusions, and mycorrhizal fungi inoculation—are improving germination rates and protecting seeds from environmental stresses, thus improving the success rates of direct seeding and offering new possibilities for forest regeneration (Pedrini and Dixon, 2020).

Advances in mechanical seeding

Direct seeding can be conducted manually or mechanically; manual methods typically are more time-consuming and labor-intensive. While earlier mechanical approaches mostly relied on tractor-mounted equipment, often of modified agricultural devices (Palma and Laurance, 2015), recent innovations have shifted more toward aerial and autonomous systems, including drone seeding and self-driving machines, offering greater precision and scalability, especially in large or hard-to-reach areas (Castro et al., 2024; Mohan et al., 2021).

Precision seeding

Precision seeding is an advanced approach to site-specific forest regeneration that uses Geographic Information Systems (GIS) and remote sensing technology to plan and carry out the seeding. By integrating detailed site assessments using geographic data, such as soil composition, microtopography, microclimatic conditions, and microsite assessment, GIS combines the information to identify the most suitable locations for different tree species. This allows for customized seeding strategies, when the aim is to establish mixed-species forests, which are more resilient to climate change, pests, and diseases (Castro et al., 2021). Additionally, by combining GIS with drone technology or other automated systems, seeding can be conducted more efficiently, covering large areas with less labor and fewer resources (Stamatopoulos et al., 2024).

Precision seeding ensures that each seed is placed where soil and environmental conditions are optimal, instead of scattering seeds randomly or systematically over the regeneration site. This approach not only improves germination rates but also reduces seed waste by limiting the seed amount sown in unsuitable locations, e.g., skid trails, natural regeneration patches, hunting rides, or exposed parent rock (Castro et al., 2023). The cost of implementing advanced GIS technology and acquiring detailed data can be high, however, particularly for large-scale projects or in regions with limited access to such technology (Oliet and Jacobs, 2012). Precision seeding also requires expertise in data analysis and equipment handling, which can increase the operational complexity. While precision seeding offers clear benefits, it is still subject to natural factors like weather and wildlife, which influence germination success. Thus, it is often used in combination with other methods to improve overall outcomes (Grossnickle and Ivetić, 2017), and careful pilot testing for locally appropriate, site-adapted application is strongly advised.

Drone-based seeding

Drone-based seeding has emerged as an innovative technique in forestry, particularly for large-scale planting projects. Drones equipped with specialized seed dispersers allow seeds to be dropped over vast and hard-to-reach areas. Advanced drone systems can be programmed to adjust flight paths based on terrain maps, ensuring that seeds are distributed evenly and in appropriate densities (Gupta et al., 2013). Drones can also be equipped to sow coated seeds that provide protection from predators and environmental stresses, giving the seeds a higher chance of survival. However, the survival of the seedlings after germination may still pose a significant challenge.

Unlike manual seeding, drones can quickly cover uneven terrains, steep slopes, or postwildfire zones that are difficult or even dangerous for human workers to access. On average, a drone can seed several hectares per hour, dispersing hundreds of thousands if not millions of seeds per day; however, the speed depends on the type of drone, the terrain, the tree species, and the scale of the project. Some larger drone systems can carry payloads of up to 10–20 kg of seeds, allowing them to cover large areas in a single flight (Vergouw et al., 2016). Drone swarms, i.e., multiple drones being used simultaneously, allow for even greater scalability, making them an efficient solution for large-scale forest restoration projects if the germination and seedling survival is sufficient to provide successful regeneration.

While the scalability of drone seeding makes it ideal for large-scale forestation projects, its precision and flexibility also make it suitable for smaller, more targeted areas (Vergouw et al., 2016). For smaller projects, drones offer several benefits, including the ability to navigate tight spaces and minimize human disturbance to the area while still reducing the labor costs and time required. Drones are ideal for restoring small plots of degraded land, creating wildlife corridors, or assisting in urban forestry projects where precision is key.

Seeding customizable seed mixes with drones is also becoming increasingly feasible and efficient. Modern drones are equipped with payload systems that can handle a wide range of seed types, from large seeds like acorns to small, lightweight seeds like birch or alder. Additionally, seed coating can help 'even out' the differences in seed size. This flexibility makes it relatively easy to seed customizable mixes with varying species in a single flight, making the establishment of mixed forest stands significantly easier.

While drone seeding offers significant advantages in terms of precision, scalability, and the ability to reach inaccessible areas, its effectiveness can be limited by factors such as payload capacity, weather conditions, and regulatory and operational restrictions. The initial cost of drone equipment and the need for repeated flights due to limited battery life can also increase operational complexity, especially when seeding larger seeds (Castro et al., 2023). Additionally, seed distribution challenges and potential seed predation are concerns that need to be managed by applying additional seed treatment measures or site management. Because drones deliver seeds to the soil surface, their advantage on inaccessible sites can be reduced by competing vegetation that restricts access to soil by seeds or by rainfall that redistributes seeds on slopes.

Hydroseeding

Hydroseeding is an innovative technique that mixes seeds with a slurry of water, mulch, and sometimes fertilizer, which is then sprayed on the soil using high-pressure equipment. This method was initially used for erosion control around construction projects but is now being adapted for forest regeneration (Brofas et al., 2007; Emeka et al., 2021). Hydroseeding can be used to quickly cover large areas with uniformly distributed seed, which improves seed-to-soil contact and promotes better germination rates (Emeka et al., 2021). The inclusion of mulch in the seed slurry also helps retain moisture and control erosion, making hydroseeding particularly effective on slopes or disturbed landscapes. Similarly to drone seeding, hydroseeding allows for customizable seed mixes, allowing for higher species diversity.

However, hydroseeding has some limitations. It requires significant water usage both during the application and sometimes also in the initial stages of seedling growth, making it a less than ideal or even unsustainable option for arid areas or places without access to irrigation. Watering after hydroseeding can be minimized by planning the hydroseeding for periods with adequate natural precipitation. Seed and mulch washout is a risk on steep slopes or during heavy rain, despite the use of tackifiers and erosion-control agents (VinZant, 2019). Additionally, while hydroseeding is cost-effective for large projects, the initial investment in equipment can be high, making it less practical for smaller areas or low-budget projects (Grossnickle and Ivetić, 2017).

Advances in seed treatment

Seed pelleting and encapsulation

One of the most significant advances in direct seeding is the development of seed pelleting and encapsulation methods, often referred to as seed coating. These coatings are designed to protect seeds from environmental stress such as predation, desiccation, and poor soil conditions, significantly improving seed survival rates and germination success (Pedrini et al., 2020). Coating the seeds can also enhance nutrient availability and control the timing of germination by providing a physical barrier that interacts with the environment (Madsen et al., 2016).

Common types of seed coatings include biodegradable or otherwise environmentally friendly materials like clay, biopolymers, and nutrient-rich compounds (Madsen et al., 2016). Some coatings are enriched with growth-promoting agents such as fertilizers, mycorrhizae, microbial inoculants, or moisture-retaining substances, helping seeds establish in degraded or harsh environments (Madsen et al., 2016; Pedrini et al., 2017). Additionally, coatings can be engineered to release seeds gradually under optimal moisture and temperature conditions, further increasing the likelihood of successful germination and seedling establishment (Afzal et al., 2020).

The thickness of the seed coating usually varies depending on the desired outcome and the conditions of the seeding site and ranges from single seed coatings of a fraction of a millimeter to seed bombs with diameters of several centimeters (usually somewhere from 1 to 5 cm). Thin coatings are often used to improve seed-to-soil contact and speed up germination under good site conditions when enough moisture is available (Madsen et al., 2016; Pedrini et al., 2020). In contrast, thicker coatings may be applied to seeds that need protection from predation or harsh environmental conditions. Thicker coatings can delay germination by controlling water absorption until conditions are favorable, giving the seeds a better chance of establishing, but often are not optimal for seeds requiring light for germination.

Seed coating also increases the weight of smaller seeds, making them easier to disperse (Taylor et al., 1998). Small, lightweight seeds (typical for many pioneer species, especially in the temperate zone) could distribute unevenly if sown by aerial methods, as they are more likely to be blown off-course or scattered (Pedrini et al., 2020). Coating them increases their mass, making it easier to spread them with precision. The use of seed coating may be restricted in the case of moist seed needing pretreatment to break dormancy at sowing time, on some sites, or both.

Seed pretreatment

Breaking seed dormancy can be necessary to ensure successful germination and establishment, either naturally by seeding when climatic conditions are suitable or by treatment prior to seeding. Traditional methods include stratification that exposes seeds to specific conditions, usually cold and moist, to simulate the natural processes required to break dormancy. Scarification is another method, used to weaken, scratch, or break the hard seed coat of certain seeds to help them absorb water and oxygen more easily. Although these methods have been used extensively, researchers and practitioners have been exploring novel methods to enhance these methods or develop new techniques that offer more efficient, reliable, and sometimes faster results.

Seed priming is one of the most used novel methods; it is a pregermination treatment that partially hydrates seeds to activate early metabolic processes without allowing seeds to fully germinate (Paparella et al., 2015). The goal is to prepare seeds for faster and more uniform germination once they are planted and is, therefore, especially helpful on sites where conditions are not ideal for natural germination, or the time of sowing does not allow for the required metabolic processes to be completed (Waqas et al., 2019). Similarly, seed priming can help reduce seed predation and seed loss prior to germination due to faster germination after seeding. Seed priming is often combined with seed batch cleaning—a process of removing empty and nonviable seeds—resulting in a seed batch that has close to 100% viable and germination-ready seeds.

There are several methods of seed priming. Osmotic priming involves soaking seeds in a solution with a compound such as polyethylene glycol that controls water potential to carefully manage water uptake (Paparella et al., 2015). Hydropriming is a simpler method where seeds are soaked in water for a brief period, then dried before sowing (Sher et al., 2019). Hormonal priming uses growth regulators like gibberellic acid (GA3) to promote early metabolic activity (Paparella et al., 2015; Rhaman et al., 2021), whereas nutrient priming involves soaking seeds in nutrient-rich solutions to boost initial seedling growth (Mondal and Bose, 2019). Biopriming uses beneficial microbes and is also increasingly popular for improving seedling establishment (Waqas et al., 2019). Thermal priming exposes seeds to high temperatures for short periods, which can break dormancy by altering seed coat structure or changing metabolic processes within the seed (Sher et al., 2019).

On the flipside, priming adds an extra step before sowing, which can increase costs and logistical complexity. Additionally, once seeds are primed, they can have a shorter shelf life because they are closer to germination (Taylor et al., 1998). The delicate balance between hydration and desiccation can make seeds more prone to spoiling, molding, or losing viability if not stored properly. If primed seeds are stored for too long or in inappropriate conditions (e.g., with fluctuating humidity or temperature), they could lose their improved germination performance and might not germinate as effectively as fresh, unprimed seeds.

Exposure to smoke or the application of smoke-derived chemicals such as karrikinolide mimics the natural ecological cues that trigger germination following a fire and has been found effective in breaking seed dormancy, particularly in fire-adapted species (Kępczyński and Kępczyńska, 2023). While primarily used as a soil amendment, biochar application has been explored for its effects on seed germination as well (Gascó et al., 2016). Mixing seeds with biochar can enhance soil microbial activity and potentially influence biochemical signals that stimulate seed germination (Thomas and Gale, 2015). Biochar can also be added to seed coatings, potentially resulting in similarly beneficial effects even when applied in small quantities.

The cost of seed treatment for breaking seed dormancy can vary widely depending on the technology involved, the scale of the operation, and the specific requirements of the tree species being treated. The previously described methods are generally affordable, with low or moderate cost points. Some other novel methods are more costly, mainly due to high initial investment into the equipment required. Some of these methods are (i) seed exposure to pulsed electromagnetic fields (PEMF) that can enhance biochemical processes within the seeds; (ii) ultrasonic treatment, which uses ultrasonic waves to create microscopic channels in seed coats that help break physical dormancy; and (iii) laser scarification, a very precise method of breaking physical dormancy using a laser to make controlled abrasions or holes in the seed coat.

Natural regeneration

Natural regeneration uses natural processes of seed production and dispersal following full or partial removal of the overstory, as well as sprouting from stumps or roots. It is an important tool for mitigating the adverse effects of climate change, because the establishment of new young stands, whether through natural or artificial regeneration, results in the binding of carbon due to the active growth of young trees (Moura Costa and Stuart, 1998; Allgaier Leuch et al., 2017). Natural regeneration accounts for over 60% of the total forest area in Europe (Forest Europe, 2020). Traditional methods using natural regeneration, such as clearcutting, shelterwood, or selective cutting, are widespread in practice (Brose, 2011; Brang et al., 2014; Kohler et al., 2020) and natural regeneration is also one of the basic segments of the concept of 'close-to-nature silviculture.' Various ecological, economic, and social requirements are the driving forces behind the shift from rotational (i.e., clearcut and plant) forestry to management techniques based on natural solutions, such as continuous cover forestry (Schütz et al., 2012; Tinya et al., 2020) or gap cutting (Madsen and Hahn, 2008; Bílek et al., 2014; Amolikondori et al., 2021) that often rely on natural regeneration.

To establish successful natural regeneration in specific situations, it is necessary to understand the numerous factors that influence it (Axer et al., 2021). Often, this knowledge is gathered from old, passively managed forests where regeneration has been left entirely to natural processes (Glatthorn et al., 2018; Feldmann et al., 2020; Kanjevac et al., 2023). The key factors necessary for successful natural regeneration include ample seed production, a clean forest floor, adequate protection (particularly from ungulate herbivory), and effective weed control during the regeneration phase (Evans, 1984). Supplemental silvicultural measures are often needed to promote development of appropriate stand structures, preserve biodiversity, maintain habitat productivity, and other ecological functions such as cycling nutrients (O'Hara, 2016). These measures can include protection from plant diseases, insects, and especially herbivores.

Restoration methods based on natural regeneration are said to be significantly cheaper than methods based on planting trees and can be applied to much larger areas, thus enabling cost-effective restoration on a large scale (Chazdon and Guariguata, 2016). This may be true if the key factors are available, in particular adequate seed sources or sprouts. However, although the initial costs of natural regeneration may be comparatively low, such stands may require intensive tending to control tree species composition, stem density, and other measures to meet the management objectives. Despite silvicultural efforts to favor desired species, naturally regenerated stands can develop with low-quality individuals, less desired species that fail to meet compositional objectives, or very dense stands that stagnate. Therefore, the lowest cost method of forestation at a particular site does not mean that it is the superior method for that site. In fact, recent analyses suggest that neither planting nor natural regeneration dominates in cost-effectiveness, and a mix of natural regeneration and planting can result in more climate change mitigation at lower costs than relying exclusively on a single regeneration method (Busch et al., 2024). An important consideration is also the resilience of naturally regenerated forests in the future climate. Natural regeneration relies on the species and provenances that are available and adapted to the current climate and conditions, preventing the opportunity to introduce material better adapted to the future.

Innovations in natural regeneration management

Successful natural regeneration may require supplemental interventions. This has been recognized with the development of assisted natural regeneration (ANR). Assisted natural regeneration is designed to remove or reduce barriers to natural regeneration (Shono et al., 2007). This method may include weeding, protection from fire or grazing, improving natural seed dispersal, and supplemental planting with desired tree species (Chazdon and Uriarte, 2016). For example, one of the methods that has emerged in practice is farmer-managed natural regeneration (FMNR) in drylands, which provides tree cover on cultivated or grazing land without planting, primarily by protecting sprouts that can develop into trees (Reij and Garrity, 2016).

Site preparation

Climate change complicates seedling establishment by increasing the frequency and intensity of stressors such as drought and heat waves. Rising temperatures accelerate seedling water loss through transpiration due to drying of the air (i.e., vapor pressure deficit), making soil moisture conservation and microclimate management critical. In regions experiencing reduced precipitation and prolonged droughts, seedlings with underdeveloped root systems struggle to access water, leading to desiccation and mortality (Grossiord et al., 2020; Novick et al., 2024). To mitigate these risks, site preparation must prioritize moisture retention techniques, such as mulching and water-retaining amendments, while also considering the influence of the overstory on microclimate conditions.

Site preparation can be particularly challenging on sites previously used for agriculture or pasture, where soils are often compacted, nutrient-depleted, and low in water retention capacity due to intensive past land use practices (Foley et al., 2005). Afforestation on abandoned farmland may face vigorous competition from existing vegetation, depending on how long the site was abandoned from active management. In such cases plowing and clearing unwanted vegetation is needed to facilitate tree establishment (Löf et al., 2012). However, in these lands the use of heavy equipment must be carefully managed to prevent further soil compaction, which can impede root penetration and limit seedling access to moisture and nutrients or accelerate soil erosion.

Mechanical site preparation

Mechanical site preparation (MSP) is commonly done prior to forestation with nursery stock or direct seeding. It aims to provide favorable spots for seedling establishment and growth (Löf et al., 2012; Sikström et al., 2020) and to increase the efficiency of the planting or seeding procedure. Methods for soil preparation vary with region, knowledge, traditions, and available machinery. Conventional MSP usually involves displacing the top organic soil layer into patches or strips, exposing the bare mineral soil or a mixture of organic matter and mineral soil. The soil can be gathered in mounds or beds or turned upside down and put back at the same location (Fig. 6.4). Specialized equipment (buckets, disc trenchers, etc.) can be mounted on various kinds of base machines (Sikström et al., 2020; Fig. 6.5). Other materials like manure or fertilizer can be applied at the same time.

Before MSP is performed, it is necessary to assess whether it is biologically, technologically, and economically feasible and what kind of site preparation would be optimal on the site in question. Conditions where site preparation could help include areas with strong vegetation competition, severe problems with pine weevils (*Hylobius abietis*), thick and inert humus layers where the roots of seedlings will struggle to reach soil layers with stable moisture conditions (especially in seeding or natural regeneration), compacted soils, soils with impeding layers that prevent the penetration of water and roots (e.g., iron pans, plow pans), or wet areas where mounding or bedding will provide dryer planting spots.

Figure 6.4 Norway spruce seedling planted after mechanical site preparation in W Norway. The seedling is treated with wax as a measure against pine weevils. Right: Scots pine seedlings three seasons after planting, SE Norway. Seedlings to the left were planted with MSP; those to the right, without MSP. *(Credit: Kjersti Holt Hanssen.)*

Figure 6.5 Mechanical site preparation using a disc trencher (left) and excavator and bucket (right) in SE Norway. *(Credit: Jan Bjørnar Sankerud.)*

Methods in mechanical site preparation

The several types of soil scarification include *patch scarification* that removes the humus layer, leaving it next to the resulting patches of bare mineral soil. It is mostly used on dry sites or on stony sites where other MSP methods cannot easily be employed. *Disc trenching* produces furrows and berms in continuous rows. This method can be applied to all types of mineral soils but is not suitable for moist sites. *Mounding* creates elevated planting spots, comprised of mineral soil usually on top of a double, inverted humus layer. The method is suitable for mesic to moist sites, where elevated planting spots are advantageous for seedling survival. *Soil inversion* refers to planting spots with mineral soil on top of an inverted humus layer. Thus, planting spots are usually level with the surrounding ground. This method can be employed at most sites, but very dry or very moist soil conditions should be avoided, as capillary water is cut off, and very moist sites need an elevated planting spot.

Subsoiling or *ripping* is used for dry soils and soils that have compact layers below the soil surface, limiting root growth and plant development. Breaking soil layers may favor root development, increasing soil macropore volume, which improves aeration, and raising moisture-holding capacity. Ripping is also used for site preparation on rocky soils that have developed from consolidated bedrock and soils with high-strength clay horizons (when dry) that may inhibit root development. Vertisols, soils with a high clay content that shrink and swell in response to moisture, are not commonly found in Europe, but they can occur in some areas with clay-rich parent materials (e.g., smectite mineralogy). Care must be taken when ripping these soils, as they may shrink along the rip when dry and expose seedling roots to the air. This can be avoided by preparing the site in the fall and allowing soil to settle into the rip before planting in the spring.

In hilly or mountainous areas with steep slopes, terracing can reduce steepness by dividing the slope into smaller, gently sloping sections that prevent rainfall runoff and accumulate soil organic carbon (Deng et al., 2021). Terraces are laid in horizontal strips of varying widths and shapes along the contour lines, separated from one another by bunds on which grass can be grown. Terracing followed by subsoiling improves water infiltration into the soil and plant root development (Querejeta et al., 2001). Terracing by hand is generally feasible and cost-effective for small-scale operations, but large equipment also is used, especially for large-scale afforestation (Çaliskan and Boydak, 2017). Terracing can enhance regional landscape diversity, provide habitats, foster symbiotic relationships among organisms, and crucially contribute to habitat reconstruction and improvement, thus maintaining biodiversity (Merino et al., 2010). Negative effects of terracing may also arise, such as interference with the hydrologic cycle caused by poorly designed or mismanaged terraces that increase soil erosion and water runoff.

Trenching along contours can be utilized on gentle slopes to capture runoff water. Trenches can be continuous, divided by cross banks, or arranged in short, discontinuous lengths with alternating gaps between rows. Runoff farming techniques can be designed to increase water infiltration and promote growth of trees and shrubs in extremely dry areas (Stavi et al., 2020).

Soil amendments

Fertilizing forest soils to accelerate growth and accumulate wood volume or carbon is practiced in many countries, with different amounts, chemical makeup, and timing, especially nitrogen (Miller, 1981; Mayer et al., 2020). Degraded soils are often low in soil organic matter (SOM), which limits water storage, nutrients, and habitat for soil organisms. Mulches, composts, and manure can increase SOM and facilitate plant establishment (Hueso-González et al., 2016) and significantly increase productivity on infertile or coarse-textured soils (Fuentes et al., 2010; Chen et al., 2018). Hydrogels embedded with nutrients can increase both water availability and nutrient supply (Coello et al., 2018; Kumar et al., 2019).

Biochar is a promising soil amendment due to its ability to improve soil fertility, nutrient retention, water-holding capacity, and overall soil health. Biochar is produced by heating plant biomass to high temperatures, between 350 and 600°C, in an oxygen-depleted atmosphere (Raj et al., 2023; Danish et al., 2014). This pyrolysis method produces a fine-grained, porous substance rich in carbon that functions somewhat like naturally produced SOM. Biochar increases carbon storage, improves the water balance, and reduces nutrient leaching (Page-Dumroese et al., 2016; Raj et al., 2023). Biochar preferably is incorporated into the soil, making it somewhat difficult on forest sites (Page-Dumroese et al., 2016), but surface application can have an impact (Palviainen et al., 2020). On afforestation sites, however, incorporation is similar to treating an agricultural soil. Biochar has been studied in boreal forests to improve seedling survival and germination rates for several tree species in northern Sweden (Gundale et al., 2016) and a naturally regenerated Scots pine (*Pinus sylvestris*) forest in Finland (Palviainen *et al.*, 2018; Zhao et al., 2019; Palviainen et al., 2020; Zhu et al., 2020). Biochar amendments may be a promising tool for enhancing soil carbon storage and fertility in forests, complementing site preparation techniques by mitigating nutrient losses during soil scarification.

Hydrogels added to soil for improving the water-holding capacity of the rooting medium are considered for restoring drylands (Chirino *et al.*, 2009; Chirino *et al.*, 2011; Ramón Vallejo et al., 2012). The added hydrogel absorbs water during rainfall and slowly releases it when the surrounding soil dries. Hydrogels have been studied for agricultural crops and could be used in the forest nursery (Chirino *et al.*, 2009; Chirino *et al.*, 2011) as well as on planting sites, although their cost-effectiveness has not been established (Hüttermann et al., 1999; Chen et al., 2004). Hydrogel effectiveness in enhancing survival and early growth (Chirino et al., 2009; Chirino et al., 2011; Hueso-González et al., 2016) could depend on soil texture. They have been effective in coarse-textured soils (Coello et al., 2018) but ineffective in clay soils (Werden et al., 2018). Additionally, hydrogels must be used with caution, as added large amounts can clump and shrink upon drying and create air-filled voids. These voids reduce root contact with soil, causing them to desiccate, resulting in early mortality (Ramón Vallejo et al., 2012).

Biostimulants are natural and synthetic compounds added to improve nutrient use efficiency. They also add nutrients. Potentially they could be used to enhance seed germination (Domínguez-Castillo et al., 2020), increase seedling drought tolerance (Tiepo et al., 2020), and fertilize soil (Vessey, 2003; García-Fraile et al., 2015). Bacteria- and fungi-based biofertilizers, fermentation metabolite-based products, humic acids, plant growth regulators, plant growth promoting bacteria (PGPB), protein hydrolysates, and seaweed extracts are some of the commercially available biostimulants. The effectiveness of biostimulants has been shown in laboratory and field treatments (Khan et al., 2015; Karličić et al., 2016; Radhapriya et al., 2018; Alves et al., 2019; de Souza et al., 2020; Padda et al., 2020; Puri et al., 2020). Inoculating seedlings in the nursery with PGPB, for example, enhances the infusion of ectomycorrhizal fungi into the root systems (Chanway, 1997), although responses are specific to plant-bacteria and genotype-genotype combinations (de Souza et al., 2020). Positive responses have been shown for *Schizolobium parahyba* var. *amazonicum* (Cely et al., 2016), *Platanus* × *acerifolia* (Karličić et al., 2017), and *Abies gracilis* (Trofimuk et al., 2020). Transplanting native soils from remnant forests may have similar effects to biostimulants (Rivas Rivas et al., 2022).

Vegetation management

Control of competition

Competition for resources (e.g., light, nutrients, and water) may also endanger seedling survival and growth during the regeneration stage (Balandier et al., 2006). Dense pioneer forests or shrublands often dominate successional stages in areas suitable for the establishment of forests. Restoring forest ecosystems in these areas may require resetting succession (Cortina et al., 2006) by reducing the dominance of pioneer trees or shrubs and reintroducing forest species of interest. Several vegetation management techniques have been applied to facilitate the introduction of new seedlings in these ecosystems by reducing competition for resources but also by restricting natural succession. The main management techniques applied are: (i) tree density reduction, which reduces the density of pioneer trees to reduce competition for resources and allow the establishment of new forest tree species; (ii) dense shrubland clipping by selective cutting in dense communities or opening new gaps where new plant species can be introduced, promoting diversity and facilitating regeneration (Pérez-Devesa et al., 2008); and (iii) weed or herb control applied in areas where competing herbaceous species may hinder seedling establishment.

Herbicides are chemicals that can be used to remove or control competitive plants without damaging the planted seedlings, to maximize seedling establishment and reforestation or restoration success. There is no chemical prescription that fits all circumstances, but the broad-spectrum herbicide glyphosate is the most used herbicide for forest regeneration worldwide. One or two applications can be sufficient to allow trees to establish. Herbicides can be conveniently used on sites too steep for machine operation. Herbicides are also effective in reducing sprouting of undesired broadleaf species.

Mechanical or aerial spraying can be used in large-scale reforestation and restoration efforts. Manual spraying is preferred in small plantings or when more control is needed, such as optimizing spray or limiting diffusion in the environment, especially into aquatic systems. In some cases, chemical treatments may increase fire risk because of the large amount of dry fuel left on the ground. Since chemical site preparation does not remove woody debris, planting may also become more difficult in comparison with mechanical site preparation (Lowery and Gjerstad, 1991), but combined use of chemical and fire treatments may reduce the woody debris. Plowing may represent an alternative to spraying to limit herbaceous competition, although it can disturb the natural regeneration and biological processes in the soil (Sampaio et al., 2007). A forestry mulcher can be used when there is much brush vegetation that needs to be treated (Jeglum, 2003). Using mulch mats to control root competition from herbaceous plants and tree shelters against predation by mammals can be expensive and inefficient (Davies, 1988; Maltoni et al., 2019).

The big challenges in the use of chemicals are the transient duration of the control effect and the negative effects of chemicals on biodiversity and human health. The efficient chemical control of weeds usually does not last for more than one growing season, and new weed seeds will soon germinate. To reduce the use of harmful chemicals in plant production systems, the European Union (EU) has established strict policies to regulate the use of pesticides (including herbicides), promoting the adoption of alternative, nonchemical control methods as a part of the integrated management of weeds, pests, and pathogens. Forest certification systems (FSC and PEFC) also advocate for the reduction of herbicide use in forestry. For the most current information on approved herbicides, it is advisable to consult the specific guidelines and lists provided by each certification body.

Facilitation

In nature, the regeneration of woody species often follows a spatial pattern associated with preestablished individuals, which suggests the prevalence of the positive nature of plant-plant interactions in nature (Brooker et al., 2008; Zamora et al., 2008). This evidence motivated the interest in the phenomenon of facilitation, which states that positive interactions between plants could be used to benefit restoration (Castro et al., 2004; Gómez-Aparicio et al., 2004; Navarro-Cano et al., 2019). Introduced nurse trees or crops (i.e., benefactors) can protect introduced species (i.e., beneficiaries) against wind, extreme temperatures, browsers, and grazers, as well as modify the water balance, provide shade, improve microenvironmental conditions, and increase soil fertility through the contribution of organic matter (Maestre et al., 2003; Gavinet et al., 2016a; Kremer et al., 2021).

The restoration of arid and semi-arid degraded environments is one of the scenarios where the greatest potential for the use of facilitation has been proven. The formation of 'resource islands' (Reynolds et al., 1999), the microclimate improvement (Breshears et al., 1998), and the positive interactions in vegetation mosaics (Callaway, 2007), make them suitable spots for the introduction of species of interest (Vallejo et al., 2000). Other ecosystems where facilitation plays a relevant role for restoration are alpine ecosystems (Aerts et al., 2007; Cavieres et al., 2014; Pugnaire et al., 2020) and highly disturbed areas, such as those affected by mining activities (Densmore, 2005; Frérot et al., 2006), all of them being environments subjected to extreme environmental conditions.

Sacrificial nurse trees—sown or planted

The concept implies establishing either sown or planted trees or shrubs in the same spot as the main tree species (crop trees). Alternatively, the crop trees can be planted into dense populations of natural regeneration, using this to protect or hide them from damaging animals. It is also described as Deer Browse Tolerant Regeneration (Rooney et al., 2015) that uses increased regeneration stock density to reduce regeneration vulnerability to deer damage, either by (1) offering alternatives to the crop trees, (2) hiding/sheltering the crop trees by the sacrificial nurse trees or shrubs, or (3) both.

Planting sacrificial nurse trees is used in practice in Denmark. For example, Sitka spruce is often the sacrificial nurse tree planted to protect the vulnerable crop tree, such as Douglas-fir. The solid evidence of cost-effectiveness is, however, lacking, and the use is very much dependent on the individual experience and evaluation by the forest manager.

Several field experiments have been installed in Denmark over the past 25 years to test direct seeding as a method for establishing dense regeneration to obtain facilitation and protection of the crop species. Nurse trees to protect against deer and nurse crops to provide shelter against harsh conditions (frost, drought, competition) are used where natural regeneration is insufficient (Fig. 6.6). For example, planted Sitka spruce has been planted as a sacrificial nurse tree to protect the crop tree (Douglas-fir) against deer browsing and/or rubbing. The method is used in practice, but cost-efficiency is not yet documented. Field experiments on an operational scale are installed and ongoing. The protection is not expected to be total but enough to prevent total girdling or destruction of the crop tree and increase its survival relative to no protection (Fig. 6.7).

There are several challenges to using sacrificial species, especially the reliability of direct seeding as a regeneration method. Rowan (*Sorbus aucuparia*) and the North American shrub species black chokeberry (*Aronia melanocarpa*) have proven good or somewhat acceptable regeneration success and cost-efficiency in regeneration when sown on sites with coniferous forests or plantations on acidic soils. The goal is not to gain protection against deer damage (browsing or rubbing/fraying) comparable to a well-managed deer fence. Rather, it is to protect and reduce damage to a level that makes the establishment

Figure 6.6 Examples of deer-browse-tolerant regeneration established in Denmark. Left: Sown (November 2013) rowan and naturally regenerated birch. Crop species are sown Douglas-fir (*Pseudotsuga menziesii* and grand fir (*Abies grandis*, left in photo), photo September 2017. Right: Rowan (*Sorbus aucuparia*) and aronia (chokeberry, *Aronia melanocarpa*) were sown as sacrificial nurse trees. The crop species beech (*Fagus sylvatica*), sessile oak (*Quercus petrea*), red oak (*Quercus rubra*), and Sitka spruce (*Picea sitchensis*, reference species) were interplanted in September 2018, four years after sowing (November 2014) of the sacrificial nurse trees. *(Credit: Palle Madsen.)*

Figure 6.7 Planted sacrificial nurse tree (Sitka spruce) protecting the crop tree (Douglas-fir) against deer browsing and/or rubbing. *(Credit: Palle Madsen.)*

and management of the sacrificial nurse trees a cost-effective alternative to fencing or using repellents. Additionally, it is attractive to keep the regeneration areas accessible for the deer and to avoid simply increasing the deer pressure elsewhere.

Management of soil water

Water availability is the main limiting factor for the success of forestation in arid and semi-arid environments and increasingly also in other areas affected by climate change. Water harvesting and conservation during seedling establishment have been practiced for many years in some areas (Tenbergen et al., 1995). Therefore, the implementation of techniques and treatments aimed at increasing the amount of effective water reaching the introduced seedlings is essential to improve restoration success. Soil moisture averaged a three-fold increase in the microcatchment in the root zone (30 cm) of narrow-leaved ash (Fraxinus angustifolia Vahl.) seedlings compared to a terrace treatment (Toprak et al., 2023). Several innovative solutions have been developed or are being tested to improve soil water management in dry areas including microcatchments for water harvesting (Fig. 6.8) and surface mulches (Fig. 6.9).

At the landscape scale in very degraded ecosystems, methods that ensure a good drainage net and minimize soil erosion, such as the Geofluv method that recognizes the importance of natural topography and erosion patterns, are highly recommended prior to planting (Hancock et al., 2019; Turrión et al., 2021). At a small scale, numerous

Figure 6.8 Constructing a diamond-shaped microcatchment in Izmir, Türkiye. (*Photo: Muhammed Ali Aydin*) Study in Türkiye are examining different shaped microcatchments to increase water retention (Esen et al., 2024).

Figure 6.9 The effect of mulching on Stone pine (*Pinus pinea* L.) seedling survival rate and growth, and soil properties in a semi-arid area in Türkiye using sawdust mulch materials and sawdust. Soil bulk density values were approximately 17% lower under 10 cm thickness of coarse sawdust, but the highest survival was with 5 cm of coarse sawdust mulch (Çerçioğlu et al., 2024). *(Credit: Melis Çerçioğlu.)*

innovative irrigation techniques, such as porous hoses, deep tubes, drip emitters, water boxes, or wick irrigation systems, have been tested in restoration projects. A combination of methods to capture runoff water, increase infiltration, and reduce evaporation could increase water availability in the planting hole. A combination of a microcatchment, a dry well filled with stones, and stone mulch at the soil surface is such an option in dryland restoration (Vallejo et al., 2012).

However, some methods are still expensive and may require extensive maintenance (Bainbridge, 2002). Valdecantos et al. (2014) reproduced some of these techniques in a restoration project developed in a degraded semi-arid area in Spain. These authors found that the 2.5 L capacity porous capsules were the most effective treatment for improving seedling survival, requiring application of only two emergency waterings during the first summer after planting.

Although still expensive, commercial products such as Groasis waterboxx, Growbox, or COCCON water boxes designed to accumulate water (from rain or from exogenous sources to the planting site) may be good solutions, depending on the species and the season (Mercé-Arévalo, 2013). The manual construction of microcatchments (i.e., two 1–1.5 m long channels on both sides of the planting hole) and the installation of plastic sheets upslope of the planting holes have been proposed as good low-cost solutions for significantly increasing the amount of water that reaches the planting hole during light rain events (Valdecantos et al., 2014; Morcillo et al., 2023). These techniques may be particularly useful in dry ecosystems where precipitation events producing runoff are scarce (Mayor et al., 2011). Contrastingly, they are not recommended in steep slopes, where the water flux concentration may entail a loss of the integrity of the planting hole structure (Smanis et al., 2021).

Another technology widely tested in areas with coastal influence is the collection of water from the fog using fog catchers. The efficiency of a fog catcher depends on the wind and fog features and on the collector's design (Regalado and Ritter, 2016, 2019). Accordingly, the registered daily rates of water collection are dramatically variable. In a review, Klemm et al. (2012) established yearly averages from 3 to 10 L m^{-2} day^{-1}; however, maximum reported values periodically reached up to 75 L m^{-2} day^{-1} in Cape Verde, Africa. Thus, there are various parts of the world where fog can represent an important part of the water input to the ecosystems, such as in the sequoia forests of California (Burgess and Dawson, 2004) or in the Canary Islands (Ritter et al., 2008). Regarding restoration projects, Estrela et al. (2009) demonstrated the suitability of using the water collected by fog catchers in restored areas in Mediterranean ecosystems. They observed not only that the collection potential of the inland area of eastern Spain was very high but also that the use of fog water in the establishment of plants for restoration purposes was an effective technique.

Impacts of site preparation

The beneficial effects of site preparation include reduced competition from other types of vegetation (Johansson et al., 2013; Nilsson et al., 2010; Nilsson and Örlander, 1999) and reduced water and nutrient stress on seedlings (Fleming et al., 1994; Grossnickle and Heikurinen, 1989). Soil scarification loosens the compact subsoil and increases soil aeration of wet soils, thus improving root growth and seedling establishment (Nordborg et al., 2003). Soil scarification can also increase temperatures in soil and at the surface, improving conditions for root growth and reducing the risk of frost damage (Burgess and Wetzel, 2000; Langvall et al., 2001). Nutrient availability is often improved because soil preparation stimulates mineralization (Nordborg and Nilsson, 2003; Nordborg et al., 2003).

Soil scarification can protect the seedlings against the pine weevil (*Hylobius abietis*), a major pest in conifer regeneration areas in Northern Europe. Adult weevils feed on the stem bark, frequently killing planted conifer seedlings (Nordlander et al., 2011). Mortality can locally be very high, and a range of measures are often necessary to bring damage down to a sustainable level. Several studies have shown that pine weevils stay for a much shorter period on pure mineral soil (Petersson et al., 2005). Site preparation methods that create planting spots covered by a mineral soil layer are found to increase seedling survival around 20%–50% in Fennoscandia (Sikström et al., 2020). Pine weevil populations will likely benefit from predicted changes to the climate (Inward et al., 2012;

Nordlander et al., 2017), and therefore MSP likely will become even more important in the future to reduce seedling mortality.

The outcomes of site preparation can, however, vary with climate and soil conditions. For instance, removal of the humus layer can increase the diurnal variations of heat flux in the soil, which can increase frost heaving in susceptible soils (Bergsten et al., 2001; de Chantal et al., 2007). Scarification or scalping that removes the humus layer may result in decreased nutrient availability in the mineral soil (Nohrstedt, 2000; Nordborg et al., 2003). In a cold and wet climate, MSP methods that increase air and soil temperature and improve soil drainage will be optimal, but on a warm and dry site, this could be detrimental. With a changing climate, we can expect tougher competition from weeds, which will make MSP increasingly appropriate in many places. The effects of site preparation on competing vegetation can be of limited duration, however, as herbs and grasses rapidly colonize the exposed mineral soil (Hanssen et al., 2003), and MSP has also been shown to increase the regeneration of competing deciduous species (Johansson et al., 2013; Karlsson et al., 2002; Nilsson et al., 2006). Site preparation potentially affects the composition of understory species for decades, decreasing species diversity and promoting survival of nonnative plants in forest stands (Šebesta et al., 2021).

In the age of climate change, it is also important to carefully consider the potential impact of site preparation measures on carbon stocks and related soil processes. A recent study in the Canadian boreal forest showed that carbon loss occurred within two years following scarification, but the impact of MSP on soil C-stocks may not be as strong as previously believed (Marty et al., 2024). Moreover, concerns have been raised about the possibility that scarification could have detrimental effects on beneficial mycorrhizal communities (Lu et al., 2018; Lazaruk et al., 2008). For instance, frequent MSPs may induce changes in the distribution of mycorrhizal spores in the soil profile, decreasing the germination rate of spores and propagules (Duponnois et al., 2001) and destroying hyphae and spores (Abiala et al., 2013). A recent study in Estonia indicated that saprotrophic fungi were negatively affected by soil scarification in Norway spruce stands but not in Scots pine stands (Rähn et al., 2023). The study also showed that fungal community composition may recover within a year after clearcutting in pine- and spruce-dominated hemiboreal forest stands. Compared to sowing, regeneration by planting after clearcutting pine stands resulted in higher richness of ectomycorrhizal fungi. However, the possible long-term effects of soil scarification on mycorrhizae are not known.

In summary, site preparation can significantly increase regeneration success (Suadicani, 2002; Granhus and Fjeld, 2008). However, the cause-and-effect relationship between MSP and enhanced seedling survival and growth is often not evident, and confounding effects can occur (Löf et al., 2012).

Advances in site preparation

On-site sensors to monitor site conditions

The ongoing digital transformation is also pushing forestry toward the use of advanced technologies and efficient collection of vast amounts of data through various sensors and devices. A key element of digital transformation is the Internet of Things (IoT) that connects sensors to the internet, enabling real-time data collection from the physical environment. Advances in wireless connectivity and AI have driven IoT applications that can support site preparation, e.g., by enabling effective monitoring of vegetation or soil moisture, which is challenging due to soil heterogeneity. While high-precision sensors like time domain reflectometry (TDR) remain costly, the adoption of low-cost electromagnetic sensors is increasing despite their lower accuracy (Bogena et al., 2017). Additionally, microbial activity, root respiration, and soil gas emissions measured with infrared and laser-based analyzers can provide indirect soil moisture insights, although energy constraints limit their use in remote areas (Torresan et al., 2021).

Improvement of site preparation machinery

Improved MSP tools have been developed to control deep-rooted competing plants and mitigate soil compaction or waterlogging while minimizing overall soil impact (Dumas et al., 2021). Mounted on lightweight, highly maneuverable excavators, these tools enable localized spot or line preparation and create intensive soil disturbances around planting spots, facilitating seedling establishment. Because they leave large undisturbed areas between spots, they cause low overall soil disturbance at the stand scale, reducing also deep soil compaction under wheel tracks (Collet et al., 2021). These tools offer a promising balance between the required intensity of localized soil disturbance and minimal stand-scale impact. Advances have also been made in introducing smart sensors for identifying suitable microsites and developing autonomous planting machines that can be programmed to follow a route and select suitable planting spots, scarify the soil, and plant the seedlings (Manner and Ersson, 2021; Södra 2023).

Guidelines

- Choose forestation methods (afforestation, reforestation, restoration) that meet the ecological or forestry objectives, such as promoting beneficial biodiversity and soil health, and consider environmental factors including soil conditions, past land use, climate limitations, and degradation processes.
- Establish mixed-species forests, which are more resilient to climate change, pests, and diseases.
- Address within-site heterogeneity by identifying landscape units and designing specific actions for each unit.

- Use natural regeneration when environmental conditions are favorable, competing vegetation and herbivore pressure are absent, and species and genetic material considered adequate for the future climatic conditions and management objectives are already present or can effectively disperse to the site.
- Mix natural regeneration and planting for climate change mitigation at lower costs than relying exclusively on a single regeneration method.
- Use artificial regeneration (planting and direct seeding) for greater control over regeneration outcomes, to introduce genetically improved stock with enhanced growth, pest and disease resistance, or climate adaptability.
- Align seedling species, characteristics, and functional traits with site conditions and balance site preparation with light and moisture availability and temperature. Match physiological characteristics of the seedling to the specific conditions of the site, linking stock type and site preparation. Use nurse trees to provide sheltered environments that mitigate abiotic stress on seedlings.
- Introduce beneficial microbiomes (plant-associated and soil microbes), organic amendments, or fertilization in the nursery or on sites to promote soil microbiome and functional processes. Enhance the presence of key microbial symbionts by amending soil or by moving healthy forest soil and the associated microbes in it from one location to another (soil transplants).
- Grow seedlings from seed treated for disease resistance, in long containers for larger root systems, drought preconditioned for stress tolerance, or with beneficial mycorrhizae for planting on dry or nutrient-poor sites.
- Utilize available digital tools, e.g., mobile phone apps for seed and seedling availability and site properties (e.g., vegetation structure and canopy openness).
- Ensure proper handling of seedlings during lifting, storage, handling, shipping, and planting operations to avoid mechanical damage to roots, dehydration of fine roots, and exposure to extreme temperatures (i.e., heat or freezing).
- Choose stock types that match site conditions. Plant stock types with a strong taproot on steep slopes or longer lateral on sites with limited water availability. Bareroot seedlings with their exposed roots often require intensive site preparation that loosens the soil, along with careful timing of planting to minimize desiccation risks. Container seedlings are more adaptable to a range of conditions and can be planted later in the season.
- Customize seeding strategies using automation and precision seeding to identify the most suitable locations for different tree species to establish mixed-species forests.
- Coat seeds with biodegradable or otherwise environmentally friendly materials, growth-promoting agents, or moisture-retaining substances to aid establishment in degraded or harsh environments.
- Prime seeds (osmotic priming, hydropriming, hormonal priming, and biopriming) to activate early metabolic processes, without allowing them to fully germinate.

- Improve germination rates and protect seeds from environmental stress by treating seed (e.g., seed coating, biochar infusions, and mycorrhizal fungi inoculation).
- Use drone systems programmed to adjust flight paths for large-scale seed dispersal in previously inaccessible or degraded areas, ensuring that seeds are distributed evenly and in appropriate densities.
- Improve data collection and monitoring using drone-assisted techniques to provide practitioners with timely information for decision-making.
- Cover large areas quickly with hydroseeding to uniformly distribute seed mixes in a slurry of water, mulch, and fertilizer, particularly on slopes or disturbed landscapes.
- Plan hydroseeding for periods with adequate natural precipitation to minimize post-planting watering.
- Selectively thin to enhance light penetration in shaded environments while preserving moisture-retaining canopy functions.
- Maintain a partial overstory on exposed sites to buffer seedlings against environmental stressors.
- Use introduced nurse trees or crops in the restoration of arid and semi-arid degraded environments, alpine ecosystems, and highly disturbed areas.
- Remove or retain shrubs as appropriate. In central and northern Europe, remove dense shrub vegetation before planting; in southern Europe, use shrubby vegetation as nurse plants.
- Use nonnative tree species as nurse trees when converting plantations of nonnative species to natural forests.
- Use drones for near-real time monitoring of artificial regeneration efforts, singly or as fleets (swarms), equipped with identical or different sensors, to allow rapid and comprehensive data collection from the regeneration area.
- Prioritize moisture retention techniques in site preparation, such as mulching and water-retaining amendments; also consider the influence of the overstory on microclimate conditions.
- Facilitate tree establishment with nursery stock or direct seeding on sites previously used for agriculture or pasture using mechanical methods to counter compaction and clear unwanted vegetation.
- Carefully consider the potential impact of site preparation measures on carbon stocks and related soil processes and use the least disturbing technique appropriate for the site.
- Use mechanical site preparation appropriate for conditions: *disc trenching* on mineral soils but not moist sites; *mounding* on mesic to moist sites to elevate planting spots; *patch scarification* on dry or stony sites where other methods cannot easily be employed; *soil inversion* on most sites, but not very dry or very moist soils; s*ubsoiling* or *ripping* for dry soils, soils that have compact layers below the soil surface, or on

rocky soils developed from consolidated bedrock and soils with high-strength clay horizons.

- Terracing (by hand in small areas or machines in large-scale afforestation) in hilly or mountainous areas with steep slopes to reduce steepness and slow rainfall runoff; subsoiling following terracing improves water infiltration and plant root development. These techniques are not recommended everywhere, for example, in Mediterranean climates with strong rains, where the effect is an increase in ecosystem degradation. Increase water infiltration and promote tree and shrub growth in extremely dry areas by runoff farming.
- Amend degraded, infertile, or coarse-textured soils low in soil organic matter with fertilizer, biochar, or biostimulants.
- Reduce dominant pioneer trees or shrubs and reintroduce forest species of interest by selectively cutting dense shrubland or using chemicals to control weeds or herbs.
- Consult forest certification bodies or government agencies for specific guidelines and lists of approved chemicals. Mechanical or aerial spraying can be used in large-scale reforestation and restoration efforts, and manual spraying is preferred in small plantings.
- Combine methods to capture runoff water, increase infiltration, and reduce evaporation to increase water availability in the planting hole, particularly in dry ecosystems. The manual construction of microcatchments is a low-cost solution.
- Use fog catchers in coastal Mediterranean ecosystems, depending on microclimatic conditions (i.e., the common presence of humid breezes from sea to land), although they are expensive and require maintenance.
- Set up an effective monitoring system that allows the status and trends of selected indicators to be measured and helps to identify the necessary corrective actions and modifications.

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