CHAPTER 7

Postplanting protection, silviculture, and management

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Introduction

As climate change and globalization intensify, tree seedlings face unprecedented stress caused by changed temperature and precipitation patterns, pests, and diseases. Warmer temperatures can increase soil aridity and seedling transpiration, intensify water stress, especially in Mediterranean climates, and constrain the capacity of seedlings to cope with natural enemies. Moreover, climate change-driven shifts in seedling phenology, such as earlier emergence and extended growing seasons, can heighten water demand and mortality risks (Hatfield and Dold, 2019; Lázaro-González et al., 2023). These factors may severely hazard the regeneration results, regardless of the planting strategies and site preparation efforts (see Chapter 6).

To support early growth of seedlings, postplanting management practices are increasingly incorporating new technologies and adaptive strategies that respond to the changing conditions. Innovative postplanting protection involves applying advanced techniques and technologies to safeguard regeneration against biotic and abiotic stresses. Several novel tools, including eco-friendly repellents, digital technologies for monitoring growth and health, and nature-based solutions to buffer for environmental stress, are now available or emerging and aim to enhance seedling survival rates and regeneration success. This chapter explores these innovations and provides insights into how forestry can adapt to meet the challenges in postplanting protection associated with climate change.

Protection against animals

Current and future threats

Nutritious seeds and seedlings are a highly attractive food source for various animals. Large herbivores, such as moose, browse on seedlings and saplings, especially during winter when other food sources are scarce. Browsing damage to the leader (apical) shoots can deform and stunt the growth of seedlings and saplings, with severe browsing potentially killing the plants. Animal damage also occurs as bark stripping by ungulates or as clipped twigs and gnawed bark by rabbits or hares, creating entry points for fungal

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Figure 7.1 Browsing by large mammals such as moose (*Alces alces*) (left) is one of the biggest problems in regeneration of northern forests (*Credit: Jesper Witzell*). Wild boar (right) digging damages tree roots. *(Credit: Johanna Witzell.)*

pathogens. Wild boars (*Sus scrofa*) consume acorns and tree seedlings and damage roots by digging, destabilizing seedlings, and affecting their growth and survival (Figure 7.1; Bongi et al., 2017). Birds and rodents consume seeds and seedlings, and even though they also disperse seeds, their consumption can significantly reduce the number of establishing seedlings (Castro et al., 1999; Birkedal et al., 2010).

Browsing by large ungulates is considered a serious threat to climate adaptation efforts in forestry. Selective browsing by ungulates in Europe, such as moose (*Alces alces*) (Fig 7.1), red deer (*Cervus elaphus*), fallow deer (*Dama dama*), roe deer (*Capreolus capreolus*), and chamois (*Rupicapra rupicapra*), can significantly shape the postplanting trajectory of forests (Olesen and Madsen, 2008; Kupferschmid, 2018; Ramirez et al., 2018). Therefore, ungulate browsing can hinder planned changes in tree species composition and disrupt climate-adapted strategies, such as establishing new tree species or genotypes through assisted migration (Champagne et al., 2021).

During the last decades, damage in forests by ungulates has dramatically increased, probably due to changes in landscape structure and social changes, such as declining recreational hunting activity (Petersson et al., 2019). This trend is common in all of Europe, including the Mediterranean, temperate, and boreal biomes (Acevedo et al., 2008; Beguin et al., 2016; Hardalau et al., 2024). Therefore, browsing seedlings has become a persistent problem in the continent, and the risk of damage to seedlings is so high that some protection methods must be implemented in most projects to make the planting viable.

Managing ungulate browsing requires a multifaceted approach that includes population management, habitat modification, stakeholder engagement, and continuous monitoring and adaptation strategies. The spatial mobility of animals and temporal fluctuations in their populations across different spatial scales make managing their impacts on forests difficult to counter. Changing climatic conditions can alter animal behavior, life cycles, and habitat use, further complicating management efforts (Cailleret et al., 2014; Spake et al., 2020). Major challenges revolve around the strong socio-economic dimension of population control. Balancing the interests of different stakeholders, including forest owners, conservationists, hunters, and the inhabitants of urban and rural areas, is complex, and conflicts are common (Loosen et al., 2021). For instance, increasing the populations of large carnivores (wolves or bears) that could control ungulates is not simple, since these animals are also a risk to public safety and livestock. Physical measures to exclude browsing animals, such as fencing, can disrupt other nontarget wildlife (Boone and Hobbs, 2004). Regulatory frameworks may restrict the methods available for managing browsing animals and can differ significantly between regions.

Repellents

Repellents are products used for protecting seeds, seedlings, and young trees from cervids (moose and deer), rabbits, and rodents (e.g., voles and squirrels). Repellents create an unpleasant sensation—such as smell, taste, fear, or irritation—that discourages the animals from approaching or consuming the treated seedlings or trees (Lindmark et al., 2020). For example, predator-based repellents trigger fear through smell, while hot chili pepper (i.e., capsaicin) induces pain upon contact, and palatability-reducing agents act via taste (Villalobos et al., 2019).

Different repellents, that is, chemical products or treatments, are available that deter or keep animals away from seedlings or young trees. Commercial repellents can be based on natural or synthetic ingredients, and their application methods (e.g., spraying) depend on the ingredient and intended mechanism. A considerable effort is being made to develop cheap and environmentally friendly repellent products. Extracts from plants containing essential oils applied directly to plants or dispersed in the air around regeneration sites have in some cases been found to deter insects and mammal herbivores (Pavela and Benneli, 2016). Other plant-derived products, such as chili pepper extract or shellfish waste (Willoughby et al., 2011; Taylor, 2014), have also been evaluated as potential, environmentally harmless alternatives. Treating oak and beech seeds with predator (mink, *Mustela lutreola*) excrement has been shown to reduce consumption and handling of beechnuts and acorns by bank voles (*Myodes glareolus*) in laboratory tests, but not in the field (Villalobos et al., 2019, 2020). Biobased and biodegradable materials tested as repellents and protectants against cervids also include unprocessed, greasy sheep wool added to top shoots of young trees (Bernacka et al., 2015).

Uncertainty about the effectiveness of natural and biodegradable repellents can vary depending on environmental conditions, such as weather and the presence of other plant species (Taylor, 2014). Repellents must be in the right place (e.g., top shoots; Figure 7.2) and at the right time, and applying repellents in the field usually requires manual labor, adding to management costs. Animals may also rapidly habituate to smell and taste

Figure 7.2 Top shoots of young Scots pine (*Pinus sylvestris*) trees sprayed with a repellent as a protection against moose browsing. *(Credit: Johanna Witzell.)*

(Villalobos et al., 2020). Ensuring consistent protection with bio-based products is thus difficult and costly, as they can require multiple applications. Moreover, although repellents are designed to be eco-friendly, there can still be unintended consequences for nontarget animals.

Integrating new innovative repellents with existing forestry practices may be difficult and require careful planning and coordination. Introducing new types of repellents to markets often requires navigating complex regulatory landscapes, leading to lengthy approval processes and a demand for extensive testing to ensure safety and efficacy. Despite the hurdles, the potential benefits of bio-based repellents make them an attractive tool for protecting young forests.

In Nordic countries, winter browsing by European moose (*Alces alces*) on young Scots pine (*Pinus sylvestris*) is a significant problem in forestry. It is known that moose avoid trees with high levels of defensive compounds that reduce digestibility. In a study conducted in Sweden (Lindmark et al., 2020), the effectiveness of Norway spruce (*Picea abies*) bark extract, rich in such compounds (e.g., tannins), as a moose repellent was tested. The extract, prepared with ethanol, was sprayed on the top shoots of young pines in winter. Treatment with spruce bark extract reduced moose browsing on the top shoots, instead directing moose to less vital side branches and nearby trees. In the first trial, using a 2.8% concentration, browsing on top shoots dropped from 15.1% to 6.8%. In the second trial, with a 5.0% concentration, browsing dropped from 19.5% to 4.7%. These findings indicate that spruce bark extract can serve as an effective, nontoxic repellent, keeping browsing below the acceptable 5% threshold and allowing most treated pines to grow undamaged to a safe height.

Fencing for protecting stands

Fences are an effective method for protecting trees from damage caused by large ungulates (Walter et al., 2010). However, the initial cost of establishing effective fences around vulnerable areas is expensive, and it is difficult to fence large areas. The effectiveness of a fence can be reduced when the targeted animal populations are large, in conditions with deep snow, or in steep terrain (Iijima and Oka, 2023). Moreover, fences require frequent, labor-intensive checking and maintenance, which adds to the costs. Fences can negatively affect nontarget wildlife and vegetation, and the wooden poles often used in forest fences are usually treated with hazardous chemicals (e.g., creosote, a potential carcinogen), adding to the negatives of traditional fencing practices.

Single-tree shelters for protecting individual trees

Individual seedling or tree protection through shelters is an alternative to area fences. Single-tree shelters (tree guards and tree tubes) act as a physical barrier that reduces animal damage, but they also strongly modify the microenvironment around the seedlings, with seedling- and site-specific implications for the growth of the seedlings. These effects must be considered when deciding between fencing and individual sheltering.

The two types of single-tree shelters are based on the material of their walls: shading nets (mesh shelters) and rigid plastic (solid wall) tubes (Figure 7.3). Both are effective against herbivory (Abe, 2022), but there are differences in their effectiveness, price, postplanting maintenance, and microclimate effects, which should provide a rationale for choosing between the materials.

Solid wall tubes restrict air flow around the seedling. Thus, they increase the daytime temperature and cause marked daily changes in air humidity, vapor pressure deficit, and

Figure 7.3 Types of tree shelters by their wall material: mesh (left) and rigid plastic (right) shelters. *(Credit: Juan A. Oliet.)*

CO_2 concentration (Oliet and Jacobs 2007; Devine and Harrington 2008; Vázquez de Castro et al., 2015), leading to changes in growth and resource allocation (Oliet and Jacobs 2007). The radiation amount and quality allowed by a translucent tree shelter depend on the transparency of the shelter walls. In a harsh Mediterranean environment, light-colored shelters that let in 60%–80% of visible light are recommended for shade-intolerant species (Oliet et al., 2021), while under the same environment, darker-colored shelters that let in 40%–60% of visible light are preferred for late successional shade-tolerant species (Oliet et al., 2003, 2019a, 2019b). These recommendations could also be applied to temperate forests that experience a summer dry period or similar conditions driven by climate change. On the one hand, light-colored, solid shelters can let in too much radiation and create high temperatures that together cause stress to shade-tolerant species (Oliet et al., 2015). On the other hand, darker shelters can inhibit root growth of light-demanding species that possess enhanced mechanisms to cope with excess radiation (Puértolas et al., 2010; Holmgren et al., 2021; Vázquez de Castro et al., 2015). Root growth inhibition in dry areas reduces drought avoidance capacity of seedlings, which can be key during the onset of summer drought (Villar-Salvador et al., 2012).

Ventilation is an important feature of shelters. Solid wall tubes can be ventilated (with openings) or unventilated (closed). Without ventilation, photosynthesizing seedlings can exhaust CO_2 concentration within the shelter already by early morning, especially in wet and temperate mesic conditions (Dupraz and Bergez 1999; Bergez and Dupraz, 2000; Pemán et al., 2010). High summer temperatures in nonventilated tubes can also reduce seedling photosynthesis (Mayhead and Jones 1991), leading to reduced biomass and diameter of sheltered seedlings, which is often observed on mesic sites (Devine and Harrington 2008; Mariotti et al., 2015). To avoid this problem, ventilation (holes in the walls) is usually beneficial (Bergez and Dupraz 2009). With slow-growing species in dry areas, the reduced access to CO_2 is not a major problem (Oliet and Jacobs, 2007), but extreme temperatures that can develop in tubes cause stress. In ventilated shelters, temperature is significantly lower than in close-walled ones during the whole year (Mechergui et al 2019). Microclimate is more intensely altered in the tubes than in meshes, as the latter only reduces incident radiation, specifically if the matrix size is smaller than 0.8 cm (Devine and Harrington 2008; Navarro-Cerrillo et al., 2021).

Along with the wall material, a shelter's height is crucial for its effectiveness. Commercial specifications suggest 0.6 or 0.75 m for rodents (rabbits, hares, etc.) or wild boars, while for ungulates and cattle, the height ranges between 1.2 (sheep, goats, chamois, and roe deer) and 2.1 m (moose, red and fallow deer) (Van Lerberghe, 2014; Figure 7.4). Combined results from several studies suggest that 1.5 m is the most effective height against damage by deer (Redick and Jacobs, 2020).

The choice of shelter type must consider the specifications discussed above, together with site- and species-specific information. Both the mesh and solid wall tubes provide protection against excess radiation (Puértolas et al., 2010), but in areas with persistent

Figure 7.4 The shelters and mesh size must fit the size of the predator: 2 m-tall shelters protect against deer (upper left), and 0.6 m-tall tubes in a landscape overrun by rabbits (upper right). *Sorbus torminalis* is free from roe deer browsing when protected with a 1.8 m tall shelter (lower left). Tall mesh shelters are also used to prevent deer damage (lower right). *(Credit: Juan A. Oliet and D.F. Jacobs, lower right.)*

strong winds, solid wall tubes improve seedling survival compared to plants protected by mesh (Valenzuela et al., 2018; Oliet et al., 2019a). Comparative studies in harsh environments suggest that solid wall tubes outperform mesh tubes in plant survival (Padilla et al., 2011; Oliet et al., 2019a). On the contrary, meshes are preferred over solid walls in humid, temperate environments, where the intensity of abiotic stress is milder (Redick and Jacobs, 2020; Acevedo et al., 2020).

In general, angiosperm species are positively affected (higher survival) by tree shelters, while conifers show a lesser effect on survival when compared to nonprotected seedlings (Abe, 2022). Early successional, light-demanding species such as Mediterranean pines survive better in open meshes (matrix size larger than 0.8 cm) than in solid wall tubes (Oliet et al., 2023). However, in contrast to solid wall tubes, mesh tubes require regular site inspections at a higher frequency to straighten, repair, or replace parts damaged by animals or strong winds (Van Lerberghe, 2014). Additionally, solid wall tubes provide more permanent protection against browsing (Thyroff et al., 2022) and branch deformation (Oliet et al., 2023), also facilitating herbicide application for weed control and other tending operations (Graf et al., 2022). These characteristics could offset the more expensive solid wall tubes, although a specific cost-benefit analysis must be conducted for every planting project. Van Lerberghe (2014) compiled a detailed manual about using meshes in forest restoration in Europe.

The life span of shelters needs to be factored into the choice. Protection is effective for about five years on average, but this depends on the site, shelter, and pest species. Tall shelters against cattle or deer (1.5 to 2 m tall, see above) need to remain longer than the short 60 cm ones used against rodents. Because shelters confer a slender stem shape during the first years, trees should remain in the shelters until crown morphology is balanced to avoid the risk of falling over or stem breakage (Figure 7.5). This occurs sooner with mesh than solid wall tubes, where trees can require as long as 14 years under semiarid conditions, although this period can be shortened for other species and biomes (Oliet et al., 2023 and references therein).

Figure 7.5 Shelters confer a slender stem shape during the first years, and therefore trees should remain in the shelter until the tree crown morphology is balanced to avoid the risk of falling over or stem breakage. *(Credit: Juan A. Oliet.)*

Guidelines for choosing tree shelters or fencing

The decision between shelters and fencing is complex, involving at least four groups of factors to consider:

Economy

An economic appraisal must be made, considering planting design, operational costs (including removing shelters or a fence), subsidies, and other specific details (Graf et al., 2022), including long-term maintenance expenses. In general, the decision to fence versus individual shelters is mediated mostly by planting density and shape of planting area. The higher the planting density, the relatively cheaper the fencing is.

Ecological effects

Every protection method has an impact on the environment. In addition to the negative effects of residues of shelters or removal of fences, fencing has other potential site-specific implications: fencing restricts land use (Van Lerbherghe, 2014) or may have a negative impact on the landscape and wildlife due to fragmentation. Additionally, some plant communities in pastures are shaped by livestock feeding and thus can degrade when animals are excluded.

Demands of the protected tree species

Consideration should also be given to the species mix in the project and to the effect of tree shelters on growth and survival. As mentioned above, tree shelters change microclimate. For the shade-tolerant species, tree shelters can improve planting success. The increased survival within tree shelters can be over 30% under harsh environments due to reduced abiotic stress (Navarro-Cerrillo et al., 2021; Piñeiro et al., 2013).

Type of animals

The type of threat affects the protective solution adopted. Fencing is mostly effective for cattle and ungulates (for deer, see Redick and Jacobs, 2020), but not for rodents (Castro et al., 2015). Reducing the matrix at the bottom of the fence can reduce, but not fully exclude, the entrance by small rodents. This type of fencing is also more expensive. Shelters provide limited protection against wild boars, and the patchy, unpredictable rooting by boars across the landscape makes the use of shelters even less reliable.

Future-oriented solutions for protection against animals

Innovations in developing repellents focus on biodegradability, aiming for products that break down naturally in the environment, reducing the pollution risk and long-term ecological damage (Pirzada et al., 2020). Biodegradable polymers (polysaccharides, proteins) or plant-based gels can be infused with natural repellents and applied as a coating on plants or applied in soil around the seedlings. As the polymer or gel degrades, it releases the repellent gradually, providing a longer release and protection time. Drones equipped with repellent dispensers may be used to precisely release natural enemies and/or precision sprays of pesticides quickly and efficiently (Iost Filho et al., 2020). Using systems where sensors (cameras) detect herbivore presence and trigger on-site release of repellents automatically (Internet of Things, or IoT technology) are likely to become more common soon (Wang et al., 2024). A targeted approach could minimize the amount of repellent used and reduce environmental impact.

Petrochemical plastics are the most frequently used materials for both solid and mesh shelters in Europe (Graf et al., 2022). There is an emerging concern about the use of plastics due to their high carbon footprint and the harmful environment impacts (Arnold and Aston, 2012). The plastic of tree shelters, if left abandoned in the field, is degraded via photo-oxidation and broken into small particles, leaving some microplastics that are dangerous for the environment (Ng et al., 2021, Figure 7.6). A solid tube has a mass of around 100–150 g. Considering the density of 1000 trees ha^{-1}, the plastic mass from shelters left in a planting can be around 120 kg ha^{-1}. To reduce the pollution from using shelters, they should be removed and recycled when they are no longer needed and before they degrade. However, especially in changing climatic conditions, this is challenging, as there is no reliable information about the expected duration of commercial products. Consequently, shelter removal from the field is uncommon, despite European regulations (EU Plastic Reduction Directive; Graf et al., 2022). Regulations should therefore incorporate necessary funding to incentivize the removal of shelters as part of tending operations. In addition, reliable information about the durability of the materials used in shelters needs to be made publicly available (Graf et al., 2022). Another way to improve sustainability is to construct shelters with materials that biodegrade in the soil after their protection function is fulfilled. Currently, however, there is neither a clear definition of complete biodegradability nor an array of materials that offer adequate durability in different environmental conditions (but see Graf et al., 2022).

Figure 7.6 Plastic tree shelters photo-oxidize (degrade) and break into pieces, losing their ability to protect the seedlings or to support them if degradation is premature. *(Credit: Juan A. Oliet.)*

Managing the threat of emerging and introduced pests in forestation

Current and future threats

Seeds and seedlings with their high nutritious value are vulnerable to biotic damage caused by pathogenic microbes, insects, or nematodes (hereafter referred to as 'pests'). Climate change and globalization are also increasing the risk of outbreaks and epidemics of new pests in forest settings. Alarmingly, international trade and transportation of plant material, such as living seedlings and seeds, have been identified as significant pathways for introductions (Hulme 2009; Guégan et al., 2023; Franić et al., 2024). Moreover, new pests can be introduced in ornamental plants, which are often imported and planted in public green areas and private gardens, from where they may spread to surrounding forests. Abiotic stress and forestland degradation increase the vulnerability of trees to pests.

Recent examples of destructive, introduced pests in Europe include the fungal pathogen *Fusarium circinatum* that infects pines of all ages, including seedlings (Figure 7.7). In addition, fungal-like (Oomycete) pathogens in the genus *Phytophthora* (Lopez-Garcia et al., 2024) are threatening forests, along with insects such as the emerald ash borer (*Agrilus planipennis*) (Orlova-Bienkowskaja et al., 2020) and bronze birch borer (*Agrilus anxius*) that could find their way to European forests in the near future.

Emerging pests include nonnative or native pathogens and insects that cause increasing problems due to the changing environment. Their emergence can be local or occur over a large area. *Diplodia pinea* is an example of this type of pathogen. It causes Diplodia tip blight disease in conifers, but the fungus can also be present in the tree without causing disease symptoms (Fig 7.7). Warmer temperatures have been identified

Figure 7.7 Examples of introduced diseases and pests: Left: Pine seedlings killed by *Fusarium circinatum*. (*Credit: Julio Diez*) right: Diplodia tip blight on scots pine. *(Credit: Johanna Witzell.)*

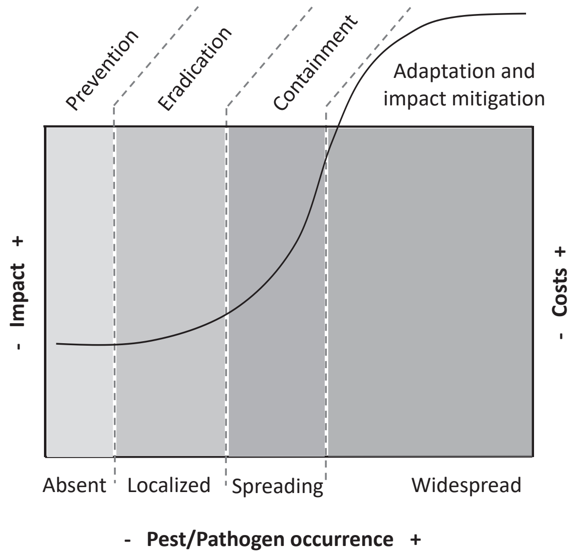

Figure 7.8 Schematic representation of the different phases of pest or pathogen invasion. *(Credit: modified after DPI Victoria, 2010.)*

as a driving force behind the emergence of this pathogen. Changing climate has also increased damage by native bark beetles (*Ips typographus, Polygraphus poligraphus*) that occur mainly in mature conifer forests (McVicar et al. 2012; Venäläinen et al., 2020).

Different tools and measures are needed for various forest conditions and during the different phases of epidemics and outbreaks (Figure 7.8). Rapid and accurate methods for early detection and availability of resources for acute operations are key challenges in prevention and eradication. Eradication of insects that are easier to detect before they spread widely can in some cases be successful (Marchioro and Faccoli, 2021), but microbes such as fungal pathogens may stay undetected (latent) and spread widely in the environment, making eradication impossible. Experiences with introduced fungal diseases such as Dutch elm disease (caused by fungi in the genus *Ophiostoma*) show that, despite often encouraging initial results, the complete eradication of established diseases is generally unachievable.

Innovative protection and control against pests and pathogens

The best way to safeguard forestation against introduced pests and pathogens is by preventing their entry (Finnoff et al., 2007). Border controls are therefore crucial, but it is challenging—often impossible—to detect tiny pests and pathogens within large plant or seed shipments, packaging materials, or containers (Kompas et al., 2023). Even asymptomatic plants can host hidden (latent) infestations, underscoring the importance of continuous surveillance for effectively controlling and managing emerging pests and pathogens. In response to these challenges, several innovative solutions have been developed for the on-site detection and management of harmful organisms. The most desirable characteristics of these tools include affordability, portability (e.g., hand-held devices), rapid detection capability (ranging from minutes to a few hours), and ease of use, requiring minimal expertise for operation and data interpretation. The following section highlights some innovative methods, both available and close-to-market, for the early detection of introduced pests and pathogens.

Detection methods

Volatile organic compounds (VOCs) emitted by pests and pathogens can be detected as specific indicators of their presence (MacDougall et al., 2022). In addition, infections may induce emission of volatiles from the host plant, providing an early warning signal that prompts more detailed examinations using other methods (Favaro et al., 2024). VOCs can be collected nondestructively (without damaging or killing the analyzed plants) from many plants simultaneously, which makes the method useful in nurseries or at border controls. An 'e-nose' (electronic nose) is a portable device that mimics the human or animal sense of smell (Ali et al., 2023). It is constructed of a sensor array that can detect and analyze the volatile compounds present in the environment. The e-nose advantages over traditional chemical analysis methods include the possibility for real-time monitoring, nondestructive sampling, and the ability to detect complex odor mixtures. Volatiles can also be detected by sniffer dogs trained to find certain volatiles specific to forest tree pathogens, such as soil-borne *Phytophthora* (Carter et al., 2023), or insects such as bark beetles (Vošvrdová et al., 2023).

Molecular methods based on DNA sequencing have become key technologies in the detection and diagnosis of plant diseases, also allowing the identification of genes that are associated with phenotypic traits in pests (e.g., aggressiveness). Loop-mediated isothermal amplification (LAMP) has recently emerged as a rapid and sensitive molecular biology technique used for detecting pathogens (Aglietti et al., 2019). LAMP assays are highly specific and can detect target DNA sequences with high sensitivity, making them suitable for on-site detection of pathogen species. The simplicity and rapidity of LAMP make it particularly useful in resource-limited settings where access to sophisticated laboratory equipment may be lacking. Recent development of the so-called 'third generation sequencing platform' (Oxford Nanopore Technologies) has opened up further possibilities for rapid, on-site diagnostics of pathogens (Chalupowicz et al., 2019). It has proven useful, for example, in detecting *Xylella* bacterium (Faino et al., 2021) and fungal and oomycete pathogens (Loit et al., 2019).

Monitoring methods

Effectively managing biotic threats in nurseries and plantings necessitates frequent and accurate monitoring, which involves systematic observations of the damage and causal agents. Monitoring enables the early detection of outbreaks, facilitating timely interventions that can prevent substantial damage. Traditional methods, such as visual inspections and manual counting, are increasingly being complemented or replaced by advanced technologies that deliver real-time data, enhance detection accuracy, and reduce labor costs. For instance, a multispectral, 3D scanner can provide accurate data on both physiological and morphological traits of plants, detecting early stages of stress or damage (Figure 7.9). While these scanners are currently suitable mainly for nursery conditions, the technologies are at a level that will allow field applications to develop in coming years.

Proximate and remote sensing are powerful tools in modern forest protection, utilizing different sensors (thermal, RGB, multispectral, and hyperspectral cameras), satellites, drones (UAV) (Figure 7.10), and other aerial platforms to gather data about damage occurrence over large areas (Liu et al., 2019). These systems can autonomously detect and identify pest species, count the number of individuals captured, and transmit the data via wireless networks. Smart traps combine traditional trapping mechanisms with advanced sensors (cameras), smart devices (IoT), and machine learning (image recognition algorithms). These systems can autonomously detect and transmit the data via wireless networks. Smart traps enable precise, near real-time monitoring of pest populations and can trigger alerts when pest numbers exceed threshold levels, facilitating immediate action. Limitations are the still rather high costs, the need for a power supply, in some cases the low picture quality, and the need to improve algorithms (Preti et al., 2021; Petso et al., 2022).

Figure 7.9 A multispectral 3-D scanner can rapidly collect large amounts of data that reveal early color changes caused by stress or infection in seedlings. Software translates the data to indices (e.g., NDVI) that can be used to evaluate plant condition. *(Credit: Daniel Knapp, Linnaeus University.)*

Figure 7.10 Drones equipped with cameras have become an affordable monitoring tool for many forest owners. *(Credit: Basam Dahy, Linnaeus University.)*

Citizen science, the voluntary engagement of people in collecting data for scientific research, has emerged as a complementary tool for detecting and monitoring pests and pathogen damage (de Groot et al., 2023). Phone apps and web platforms such as TreeAlert (www.treealert.forestresearch.gov.uk/), Silvalert (https://app.silvalert.net) and Observatree (www.observatree.org.uk) have been used for awareness raising and collecting records about tree pests.

Environmentally friendly treatments

Environmentally friendly control methods are becoming increasingly important in forestry, where maintaining tree biodiversity coincides with growing restrictions on pesticide use. Biological control, or biocontrol, involves using ecological relationships between pests and their natural enemies (natural predators, parasites, or pathogens) to manage pest populations. The method offers a sustainable alternative to chemical pesticides, as it promotes biodiversity and reduces the risk of pest resistance and is thus a key component of integrated pest management strategies (Sweeney et al., 2023).

In forestry, a widely used biocontrol method is applying the fungus *Phlebiopsis gigantea* (Rotstop) on freshly cut stumps to prevent root and butt rot fungi (*Heterobasidion* species) (Drenkhan et al., 2022). Commercially available biocontrol products (e.g., Mycostop) have been reported to potentially control gray mold in pine seedlings in forest nurseries (Capieau et al., 2004). Only a few other biocontrol products for forests have so far reached the market, despite the potential shown in tests. For instance, to control the pine weevil (*Hylobius abietis*), investigators have used nematodes of the species *Steinernema carpocapsae* and *Heterorhabditis downesi* (Kapranas et al., 2017) and fungi in the genera *Beauveria* and *Metarhizium*, applied in aqueous suspensions or as spores (fungi) around stumps to target developing larvae and pupae. Hamberg and Hantula (2016) reported a fungal treatment (*Chondrostereum purpureum*) to suppress unwanted sprouting of deciduous trees in forest regeneration areas. In addition, a successful way to control chestnut canker disease (*Cryphonectria parasitica*) involves using hypovirulent strains of the fungi infected by the CHV1 virus (Zamora *et al.*, 2012).

Protection against pests can also be achieved with low-risk plant protection products. These can be based on different active components, including plant or seaweed extracts, signal compounds that guide insect behavior, or microorganisms (Lankinen et al., 2024). With their natural origin, lower toxicity levels, and biodegradable composition, they are less likely to accumulate in the environment compared to conventional pesticides. Using low-risk products implements the EU ambition to minimize the negative impacts of pest control on nontarget organisms and ecosystems. Nevertheless, the definitions and regulations for their production and use need to be streamlined before more products can be available in the markets (Lankinen et al., 2024).

RNA interference is a novel technique where externally applied (e.g., sprayed, injected, or added by soaking the roots) RNA (a molecule that copies genetic instructions from DNA and helps cells build proteins) specifically targets and shuts down genes in pests or pathogens that are important for their activity and survival. Thus, the treatment helps to suppress and control target pest populations (Singewar and Fladung, 2023), offering an economic and ecological form of pest control that minimizes harm to nontarget species and reduces the need for broad-spectrum pesticides (Sellamuthu et al., 2024). Importantly, gene silencing with externally added RNA molecules is not a GMO technique, and thus it represents a promising addition to the forest protection toolkit. This technique was recently demonstrated to be effective against pine pitch canker caused by *Fusarium circinatum* (Bocos-Asenjo et al., 2024). Active research is carried out to solve technical problems, especially in delivering RNA to pests and pathogens, and practical applications may be available in coming years.

Silviculture for postplanting control of pests and pathogens

Postplanting management involves silvicultural interventions designed to enhance the growth, health, and resilience of established seedlings and young trees. Trees planted in unsuitable conditions are more vulnerable to pests and diseases, and not all errors in site preparation and planting or direct seeding can be fixed after the fact. Therefore, the success of postplanting silviculture begins with carefully matching species and site, and ensuring that soil type, drainage, protection, and nutrients are as optimal as possible for the growing seedlings.

Choosing the right genetic material is vital in minimizing postplanting pest and pathogen problems (Chapter 5). Planting a species mix rather than a monoculture can in some cases reduce the risk of widespread pest and pathogen outbreaks; selecting genetically diverse and resistant varieties can increase overall resilience (Jactel et al., 2021).

Breeding programs aimed at enhancing resistance to specific pathogens or pests can provide planting stock that is less likely to suffer severe damage (Sniezko, 2006), although most breeding programs are primarily focused on productivity or wood quality. Recently, the concept of microbiome-assisted breeding has emerged (Gopal and Gupta, 2016), suggesting that a targeted approach during plant breeding can also support the development of healthy and plant-beneficial microbial communities on the seeds.

Planting density and spacing are critical factors that influence the microenvironment within a planting, also impacting the spread and severity of pests and pathogens. Proper spacing between trees can improve air circulation, reduce humidity levels, and limit spreading pathogens that thrive in crowded, moist environments. Adequate spacing also reduces competition for resources, allowing trees to grow more vigorously and withstand pest attacks better. As trees mature, thinning operations may be required to maintain optimal spacing and reduce competition. Removing diseased or pest-infested trees in thinning operations can reduce the spread of pathogens or pests to healthy individuals. Thinning supports growth and vigor of residual trees, making them more resistant to damage by insects and pathogens, although this may depend on tree and pest species (Moreau et al., 2022).

Sanitary practices, such as regular pruning to eliminate dead or diseased branches, can help to prevent pathogen transmission. Moreover, removing harvest slash that may harbor pests may be needed to maintain seedling health, especially important in areas previously affected by epidemics. The fungus *Gremmeniella abietina,* responsible for Scleroderris canker, shoot dieback, and death of pine trees in forests and tree nurseries (Romeralo et al., 2023), hit pine forests in Sweden during the early 2000s. Scots pine (*Pinus sylvestris*) seedlings were planted within a year after sanitation felling. One year postplanting, spore-producing structures were present on 32% of the control seedlings, and seedling mortality was 15%, with 10% attributed to *G. abietina* (Bernhold et al., 2006). Removing and piling the infected slash reduced seedling infection rates by 50% and mortality by 27% compared to the control. To further mitigate infection risks, the authors suggested delaying planting, burning slash, or completely removing infected slash (Bernhold et al., 2006).

Targeted removal of vegetation in the vicinity of the forestation field can suppress certain diseases. Rust fungi are a group of pathogens that infect economically useful trees but also need another plant species to complete their life cycle. Such fungi are, for example, the causal agent of pine twisting rust (Melampsora pinitorqua) that affects young Scots pine and uses European aspen (Populus tremula) as its alternate host; the fungus that causes Scots pine blister rust (Cronartium pini) alternates on several plant species (Kaitera et al., 2015). Because the switch between the two hosts (host alternation) is critical for completing the pathogen's complex life cycle, eliminating the alternate host in the vicinity of forest stands can help to disrupt the disease cycle and reduce the local spore load and probability of infections. While completely eradicating alternate hosts near economically important plants is often impractical, it is important to be informed about the life cycle of pests and pathogens to avoid unnecessary risks.

Postplanting vegetation management

Competition from grasses, herbaceous species, and woody shrubs for the acquisition of major resources like light, water, and mineral nutrients is a key problem during the establishment and postplanting phases (Willoughby et al., 2009). As competitors, invasive nonnative plant species are particularly problematic. A recent report summarized invasive nonnative plants' impacts on forest regeneration in European temperate forests and found that 53 invasive species were identified as negatively impacting the regeneration of 21 native tree species (Langmeier and Lapin, 2020). For instance, the regeneration of pedunculate oak (*Quercus robur*) was adversely affected by black cherry (*Prunus serotina*) and black locust (*Robinia pseudoacacia*), but also by the perennial herb Japanese knotweed (*Reynoutria* sp.). Occasionally, however, early-successional weeds have been found to serve as natural shelters and facilitate native seedling growth in semi-arid areas if herbivory is minimal (Arias et al., 2021). In such conditions, moderate levels of herbaceous species canopy cover may help to reduce high radiation and transpiration without introducing harmful competitive effects. In most cases, however, seedling growth can be severely reduced by competing vegetation, and some form of vegetation management is needed (Willoughby et al., 2009).

Herbicides are a highly effective tool for managing a wide range of weed species. However, due to their harmful effects on nature and humans, their use is discouraged and, in many cases, banned. Forest certification programs such as FSC aim to eliminate using chemical pesticides (including herbicides) in certified forests, and the European Union's ambition is to reduce use of chemical pesticides by 50% in 2030. This has resulted in the withdrawal of many active ingredients from markets. Consequently, there is a growing demand for natural methods of pest and weed management, alongside a need for biopesticides with novel chemistries and modes of action to overcome current weed herbicide resistance issues (Mominul Islam et al., 2024; Wend et al., 2024). Bioherbicides based on natural compounds can provide a valuable tool for vegetation management, either as direct solutions in their natural state or as templates for developing herbicides with improved physicochemical properties for field application. In some cases, identifying effective herbicide target sites through natural phytotoxins can be advantageous, even if these compounds are not directly used as templates. Additionally, advances in precision and smart-spray systems can enhance the cost-effectiveness of natural product-based herbicides and microbial bioherbicides.

Supplemental planting (compensating for mortality)

Seedling mortality after planting or direct seeding occurs during the years following planting due to different causes that vary with time. Shortly after planting, typically for the first few months, seedling survival is influenced by seedling quality, weather conditions, and how well the outplanting was done. Later establishment of the planted tree becomes more dependent on how well the tree is ecologically adapted to the site conditions and whether it can survive competition and other challenges on the site (Villar-Salvador et al., 2012; Grossnickle, 2018, and references therein). Mortality (missed seedlings) due to these factors can be high, changing the specific composition and density of the initial stand. Because seedlings are very vulnerable at this stage, mortality usually occurs during the first to fifth years after planting. This shift in the projected density due to early mortality sometimes leads managers to supplement missed seedlings early to return the stand to the initial composition and density. A critical question is how much mortality must occur to justify the added expense of supplemental planting.

Answering the question of how much mortality (or the inverse, survival) there is one of the first outcomes of a proper monitoring system. Supplemental planting is therefore one of the first actions triggered by monitoring forestation and includes several tasks such as: sampling design, missed plants assessment (survey), and replanting. When a survey is conducted by traditional field methods, sampling design usually is based on a simple random sampling formula to determine sampling size. A field survey can be challenging, time-consuming, and labor-intensive, especially in hard-to-access areas. Therefore, a method to improve efficiency and reduce the costs of this task is an important innovation for the supplemental planting question. In this section, we present an innovative procedure to optimize efficiency of field sampling that is based on the World Wildlife Fund (WWF) protocol to assess missed seedlings in forest restoration projects where different species are employed (Oliet et al., 2019a, 2019b).

Using uncrewed aerial vehicles (UAV) or drones also promises to reduce the costs of detecting mortality in young plantations. However, detecting small seedlings of different species with UAVs is difficult, especially if sites are infested with weeds, multiple species were planted, tree shelters were installed, or nonuniform spacing was used. To meet these challenges, technical solutions have emerged, such as improved sensors to acquire spatial, spectral, and structural information that captures the distribution of seedlings, distinguishes between weeds and target seedlings, and detects the small trees using automated procedures (Jayathunga et al. 2023).

A protocol for an efficient procedure to assess missing seedlings in a multispecific restoration project

Objective

To properly develop a supplementary planting project, a sound survey must be undertaken to precisely estimate the number of missed seedlings. Many forest restoration projects nowadays use complex planting designs with different tree species. Determining the number of missed seedlings quickly is needed to plan for supplemental planting. This involves a sampling plan that takes into consideration this complexity while optimizing efficiency. Here we provide an example of a multispecies planting and the design of a survey to guide the supplemental planting project.

Sampling design criteria

Readers should be familiar with the principles of statistical inference and simple random sampling to gain the full benefit of this example. For background, see, for instance, Evans and Rosental (2023).

In Tembleque (Toledo, central Spain), a 10-ha restoration project was undertaken with 820 trees ha^{-1}, using six species, randomly distributed (Table 7.1, Figure 7.11). The area is homogeneous and considered a single planting unit. One year after planting, summer mortality affected the species differently, requiring supplemental planting to offset the missing plants. A survey was conducted to provide precise information on how many seedlings per species were needed.

The first step was to choose the sample size for the survey. Different formulas are useful for calculating the required sample size for simple random sampling. One equation from Avery and Burkhart (2002) for infinite populations is:

$$n = \left[\frac{(t)\cdot(s)}{E}\right]^2 \tag{7.1}$$

where E is the allowable error, s is an estimate of population variance, and t is the value from a t-distribution (approximate value $t = 2$ for a 95% probability level).

To plan this survey, survival is a binomial (categorical) variable with a variance that can be calculated as $s^2 = p\,q$, where $p =$ survival and $q =$ mortality. It can be shown that maximum variance ($s^2 = 0.25$) occurs when survival (mortality) values reach 0.5. Additionally, besides the variance, the required formula for a binomial variable needs to set the allowable error. This protocol considered a threshold of around 30% for the allowable relative sampling error for a 95% probability level. Introducing into Eq. (7.1) the threshold value of 30% relative error and the maximum variance value of 0.25 produces a subset size of around 30 seedlings for the survey of a species, with each seedling a sample unit. Therefore, sampling 30 seedlings per species guarantees a minimum precision of around 30% in determining mortality.[1]

Randomly choosing 30 seedlings (sampling units) in the planted area can be difficult. Therefore, our protocol recommends gathering these seedlings within plots. The number of plots is a function of plot size and planting density. For a high planting density, the number of plots will be lower (with a fixed plot size) than for a low planting density. As we have different species in the project with distinct planting densities, the number of

[1] According to the basic theory of simple random sampling, the error value is also affected by population size (number of planted seedlings of a species in the planted area), with sample size (number of sampling units) required to meet 30% relative error augmenting with population size. However, it can be shown that beyond a population size of 1000 seedlings in the planted area, the sample size to meet the error requirements does not increase significantly.

Table 7.1 Planned planting density in the tembleque restoration project.

Species	Planting density (trees ha^{-1})	Percentage (%)
Retama sphaerocarpa L.	198	24.2
Rosa canina L.	180	22.0
Quercus coccifera L.	162	19.8
Rosmarinus officinalis L.	145	17.7
Rhamnus lycioides L.	78	9.5
Quercus ilex L.	57	6.7
TOTAL	820	100

Figure 7.11 Restoration project in Tembleque (Toledo, Spain). The initial planting density was 820 seedlings ha^{-1}. *(Credit: Juan A. Oliet.)*

plots should vary by species. To solve this problem and improve sampling efficiency, this protocol recommends choosing one species for which the condition of sampling allowable error should be met. This is the so-called 'Less Represented Main Species' (LRMS), which should be chosen as the least abundant among the main species, meeting the following assumptions:

- Having a planting density higher than the mean density of the plantation: in our example, $820/6 = 136.7$ seedlings ha^{-1}.
- Having a planting density higher than 50% of maximum planting density. In our case, it is *Retama sphaerocarpa* L., with a planting density of 198 seedlings ha^{-1}. Therefore, the LRMS should be higher than $198/2 = 99$ seedlings ha^{-1}.
- Having a minimum density of 100 seedlings ha^{-1}.

Table 7.2 depicts the species that meet these criteria.

Table 7.2 Species of the planting project that meet the criteria to be LRMS of the survey.

Species	Planting density (Seedlings ha^{-1})
Retama sphaerocarpa	198.36
Rosa canina	180.33
Quercus coccifera	162.30
Rosmarinus officinalis	145.08

Among the species in the list, the LRMS is *Rosmarinus officinalis*, with a density of 145 seedlings ha^{-1}.

The sampling area that includes 30 seedlings of *Rosmarinus officinalis* will be:

$$Sampling\ area = \frac{30 \cdot 10,000}{145} = 2.069\ m^2$$

The number of seedlings (sampling units) that will be sampled per species will depend upon their planting density as follows (Table 7.3):

Table 7.3 Number of seedlings sampled as a function of specific density.

Species	Planting density	Sample units
Retama sphaerocarpa L.	198	41
Rosa canina L.	180	37
Quercus coccifera L.	162	34
*Rosmarinus officinalis*L.	145	30
Rhamnus lycioides L.	78	16
Quercus ilex L.	57	12

With this procedure we are sure that the more abundant species in our example (*Retama sphaerocarpa, Rosa canina,* and *Quercus coccifera*) will be estimated with a higher precision than the LRMS and the rest of the species whose importance (based on abundance) does not deserve a more intensive effort.

The number of plots to cover the surveyed area is a trade-off between economy and representativeness: the higher the number of plots, the higher the variability to cover, but also the higher the cost to move from one plot to another and set up a plot. In this case, the number of plots has a direct relationship with plot size: the larger the number of plots, the smaller the plot size for a given planting density. Plot size in forest inventory is often chosen on the basis of experience: large plots, which reduce the number of points to sample for an equal number of seedlings, are difficult to measure as plants can be missed, especially for high planting densities. But sampling error is also linked to plot size, with error diminishing with size (Avery and Burkhart, 2002). In our protocol we define a minimum value of five plots per planting unit, although in this example, we consider that this number should be raised to eight plots to get a plot size (18 m diameter) that is easier to implement and control. To avoid lack of representativeness of the sampling procedure in areas larger than 10 ha planting units, increasing the number of plots with the same size specifications, which thus increases the sampling intensity, is recommended at a rate of one plot for every additional 10 ha.

Results

We needed to compute the number of plants for the supplementary planting project. The first summer after planting, a survey was conducted, giving the following results per species (Table 7.4).

As shown in Table 7.4, the average sampling precision was high (7.6% total sampling error). All species except *Quercus ilex* and *Rhamnus lycioides* met the assumption of <30% allowable error. Fewer *Quercus ilex* and *Q. coccifera* were counted than the numbers depicted (5 seedlings vs. 12 and 11 seedlings vs. 34, respectively). This can be explained by differences between planned numbers in the restoration project and actual numbers planted of these species.

After determining mortality, the next step is to decide whether specific current density after accounting for mortality is too low considering the ecology and the function of each species in the project. In this case, overall survival is high (around 83%), but this is unevenly distributed among species (Table 7.4). For instance, mortality of *Rosa canina*, *Rhamnus lycioides,* and *Quercus ilex* is higher than that of the rest of the species whose mortality values are lower than 10%. One option could be to compensate for the mortality of the three species by planting the mortality number in the survey and not compensate for the mortality of *Q. coccifera, Retama sphaerocarpa*, and *Rosmarinus officinalis*.

Table 7.4 Survival data and calculated sampling error in the survey after the first summer postplanting.

Species	Alive	Dead	Total	Survival (%)	σ2	Relative error (%)
Quercus coccifera	10	1	11	90.9	0.08	19.1
Quercus ilex	4	1	5	80.0	0.16	**44.7**
Rhamnus lycioides	11	4	15	73.3	0.20	**31.1**
Retama sphaerocarpa	37	3	40	92.5	0.07	9.0
Rosmarinus officinalis	33	3	36	91.7	0.08	10.0
Rosa canina	25	13	38	65.8	0.23	23.4
TOTAL	120	25	145	82.8	0.14	**7.6**

Source: Real data from a survey of missed seedlings in the project.

Summary
An efficient survey designed to assess mortality in restoration projects with multiple species for supplemental planting would have the following characteristics:
- Planted area of the unit: 1–100 ha
- Allowable relative error for LRMS species: 30%
- Set size for LRMS species: 30 seedlings
- Minimum number of plots: five
- One additional plot per every 10 ha in larger than 10 ha

Guidelines

- Incorporate postplanting protection into every forest management plan. Assess site-specific biotic and abiotic risks, and budget for the required investments (e.g., fencing in areas with high browsing pressure).
- Plant mixed, genetically diverse stands. Use several species, provenances, or clones—especially resistant varieties—to build robust, resilient forests.
- Prioritize local forest reproductive material. Choosing local seed and planting stock helps prevent the introduction of new pests and pathogens.
- Optimize planting density and spacing to create a favorable microclimate, reduce harmful competition, and slow the spread of pests and diseases.
- Favor low-risk, eco-friendly protection measures. Select bioherbicides, biodegradable repellents, biocontrol agents, and nontoxic shelter or fencing materials to minimize impacts on the environment and nontarget organisms.
- Reserve broad-spectrum pesticides and herbicides as a last resort. If they are unavoidable, apply them precisely to limit runoff and exposure to pollinators and other nontargets.
- Remove and recycle any nondegradable shelters as soon as they are no longer needed.
- Match fence or shelter design to local conditions. Consider the species planted, site climate, and target animal size and behavior (e.g., darker shelters for shade-tolerant species; ventilated or mesh shelters where overheating is a risk).
- Monitor intensively for the first five years. Inspect shelters, fences, and seedling health regularly, and—when feasible—use affordable drones with RGB or multispectral sensors and mobile apps to support ground surveys.
- Analyze monitoring data to identify when supplemental planting, sanitation felling, or other interventions are necessary to curb pests and diseases.
- Carry out timely silvicultural operations such as weeding, thinning, pruning, and managing hydrology and erosion to keep young stands vigorous and resilient.
- Seek advice from forest authorities and researchers working with remote sensing and citizen science to stay ahead of pest outbreaks, population surges, and emerging threats.

- Keep up with regulations and innovations. Track new products, techniques, and policy changes to implement effective and compliant postplanting protection measures.
- Develop a postplanting management plan focusing on selecting appropriate species, planting density, and spacing to improve microclimate, reduce competition for resources, and suppress pests and pathogen spread.

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