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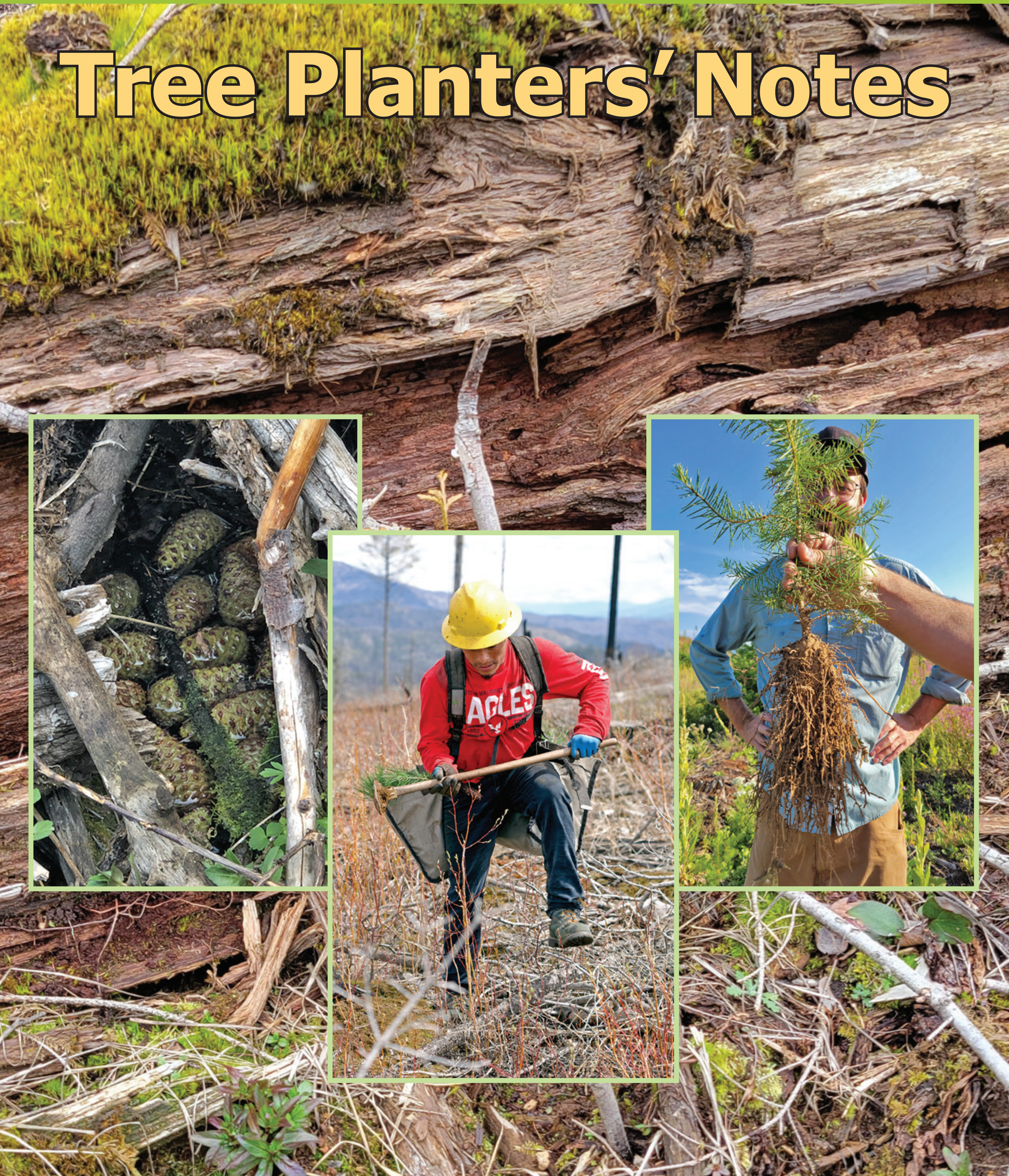
Tree Planters' Notes



Tree Planters' Notes **(TPN) is dedicated to technology transfer and publication of information relating to nursery production and outplanting of trees and shrubs for reforestation, restoration, and conservation.**

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Editor: Diane L. Haase

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Dear TPN Reader

This issue contains six proceedings articles from authors who presented at the Joint Annual Meeting of the Western Forest and Conservation Nursery Association, the Intertribal Nursery Council, and the Intermountain Container Seedling Growers Association (Missoula, MT, September 27–29, 2022). The theme of the meeting was "The Reforestation Pipeline in the Western United States." Four keynote presentations focused on each of the four aspects of the reforestation pipeline: seeds (Kildisheva et al., page 4), nurseries (Khadduri, page 18), outplanting (Altieri et al., page 28), and post-planting care (Deisenhofer, page 44). Two additional papers from that meeting provide specific topics on seed (Herriman, page 56) and outplanting (Mullane and Nelson, page 62) strategies.

In addition to the six proceedings articles, two other articles are included in this issue. Mehne and Mehne discuss strategies for establishing seedlings in conifer swamps (page 74). Bainbridge describes the use of deep roots and wick irrigation for establishing trees and shrubs on arid sites (page 87).

This issue is quite timely given the current increase in funding and program development to expand seedling production and reforestation, not just in the Western United States but worldwide. Such efforts are needed to counteract accelerated forest losses due to wildfire, climate change, pests, diseases, extreme weather events, and other damaging factors.

Best wishes for a great tree planting season!

Diane L. Haase

For in the true nature of things,
if we rightly consider,
every green tree is far more glorious
than if it were made of gold and silver.

— Martin Luther

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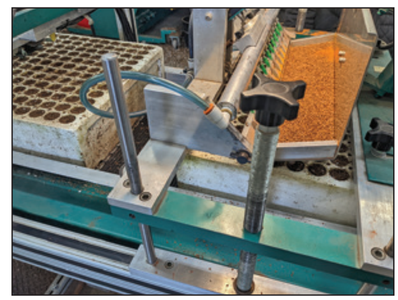

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Got Seeds? Strengthening the Reforestation Pipeline in the Western United States

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Abstract

Healthy forests are critically important for mitigating the effects of climate change, reducing biodiversity loss, and protecting our water resources. Decades of chronic underfunding combined with the worsening impacts of climate change and wildfire have increased the need for reforestation across the Western United States. This article highlights the challenges impacting tree-seed availability and suggests opportunities for strengthening the tree-seed supply chain to meet reforestation goals in an era of climate change. This paper was presented at The Reforestation Pipeline in the Western United States–Joint Annual Meeting of the Western Forest and Conservation Nursery Association, the Intertribal Nursery Council, and the Intermountain Container Seedling Growers Association (Missoula, MT, September 27–29, 2022).

The Need for Reforestation

Forests provide critical ecosystem services and reduce the impacts of the dual crises of climate change and biodiversity loss through sequestering atmospheric carbon dioxide, provisioning clean water, supporting ecological function, and maintaining biodiversity (Domke et al. 2020, Griscom et al. 2017, Liu et al. 2021, Pörtner et al. 2021, Stanturf et al. 2014). For these reasons, sustaining healthy and functional forests is paramount.

Natural forest regeneration is progressively impaired in many places due to increasing trends in temperature and drought, especially following wildfires (Coop et al. 2020). Wildfire in the United States now regularly burns more than 10 million ac (4 million ha) annually (Abatzoglou and Williams 2016, Hoover and Hanson 2022). In the last few decades, the extent of western wildfires has doubled in California alone, approximately 1 of 8 acres of forestland has burned in the last decade (Rogers and Wei 2021). These wildfires are burning with higher intensity and severity than in the past, which can diminish the extant seed bank, reduce seed rain, increase soil hydrophobicity, and ultimately limit natural regeneration (Harris et al. 2021, Madsen et al. 2012, Thays dos Santos Cury et al. 2020). The synergistic effects of climate change and biological pressures, which can act as drivers of condition change or forest-type conversion, are also increasingly apparent across western forests (Dumroese et al. 2019, Stevens-Rumann et al. 2017, Stevens-Rumann and Morgan 2019). For example, climate change is driving the increased presence of bark beetles across wider elevation bands, thereby expanding the extent of wildfire, and, in turn, limiting natural regeneration (Larvie et al. 2019, Nigro et al. 2022).

Active reforestation efforts are increasingly needed to counteract accelerating forest losses and mitigate current and future carbon dioxide emissions. A recent study suggests that at least 64 million ac (26 million ha) of natural and agricultural lands have the potential to be reforested in the United States (American Forests 2021, Fargione et al. 2021). Achieving this goal by 2040 would require planting 30 billion trees, a twofold increase in annual seedling nursery production. For the contiguous Western United States (which included 15 States in the study; table 1), the reforestation potential is approximately 24 million ac (10 million ha) and would require 7.5 billion seedlings. According to American Forests (2021), the reforestation opportunity is approximately equal between private and

Table 1. Reforestation capacity and seed need estimates for an ambitious reforestation scenario for the contiguous Western United States vary among States (adapted from Fargione et al. [2021]).

State	Reforestation on pasture and marginal cropland	Reforestation on natural lands	Total reforestation	Number of trees[a]	Approximate number of seeds needed[b]	Approximate mass of seeds needed[c]	Approximate mass of seeds needed[c]
	(1,000 ha)	(1,000 ha)	(1,000 ha)	(millions)	(millions)	(1,000 kg)	(1,000 lb)
Arizona	4	522	525	389	428–2,334	6–49	13–107
California	260	596	856	635	699–3,810	9–80	20–175
Colorado	94	1,090	1,183	877	965–5,262	13–110	28–242
Idaho	254	900	1,155	856	942–5,136	12–107	28–236
Kansas	262	250	512	380	418–2,280	6–48	12–105
Montana	175	993	1,168	866	953–5,196	13–108	28–239
Nebraska	41	346	387	287	316–1,722	4–36	9–79
Nevada	50	380	430	319	351–1,914	5–40	10–88
New Mexico	10	819	828	614	675–3,684	9–77	20–170
North Dakota	61	133	195	144	158–864	2–18	5–40
Oregon	169	191	360	267	294–1,602	4–33	9–74
South Dakota	86	568	655	485	534–2,910	7-61	16–134
Utah	48	785	832	617	679–3,702	9–77	20–170
Washington	134	104	239	177	195–1,062	3–22	6–49
Wyoming	105	641	746	553	608–3,318	8–69	18–153
Total	**1,753**	**8,318**	**10,071**	**7,466**	**8,215–44,796**	**110–935**	**242–2,061**

[a] The values for the number of trees per area were identified through surveys.

[b] The approximate number of seeds needed was calculated based on the range of 1.1:1 to 6:1 seed-to-shippable seedling ratio estimates derived from Griffis and Lippitt (2021) and Bonner and Karrfalt (2008) for container seedlings.

[c] The approximate mass of seeds needed was calculated using the following formula: germination (%) x purity (%) x seeds kg^{-1} x yield (%) x shippable (%) (with germination = 80 to 95 percent, purity = 80 to 95 percent, seed mass = 26,000–84,336 seeds kg^{-1}, yield = 60 to 100 percent, shippable seedling factor = 80 to 90 percent [values were derived from Bonner and Karrfalt 2008]); seed mass ranges were based on commonly produced conifers.

public lands. Despite this growing need and interest in reforestation, the capacity to reforest has remained limited (Dumroese et al. 2019, Fargione et al. 2021). For example, over the past several decades, the U.S. Department of Agriculture (USDA), Forest Service, which manages 193 million ac (78 million ha) nationally (Dumroese et al. 2005), was only able to reforest an estimated 15 to 20 percent of national forest lands requiring reforestation annually, which accounted for 6 percent of areas in need of reforestation after wildfire (Dumroese et al. 2019, USDA Forest Service 2022).

Recent policy changes and increases in funding offer an opportunity to address national reforestation needs. For example, the Repairing Existing Public Land by Adding Necessary Trees (REPLANT) Act of 2021 permanently lifted the spending cap on the Reforestation Trust Fund, which will help support planting 1.2 billion trees by 2031 to address the growing reforestation backlog on land managed by the USDA Forest Service (Balloffet and Dumroese 2022). In addition, the Bipartisan Infrastructure Law (Public Law No. 117–58), the Inflation Reduction Law (Public Law No. 117–169), and several State policies have also made funding available to support reforestation in the near term. In the private sector, an influx of companies has pledged to go carbon neutral or negative, with 42 percent of global offset credits attributed to forest carbon projects between 2015 and 2019 (World Bank 2020). These reforestation-based, carbon-offset projects are being implemented through various methodologies by private and public entities, including industrial forestry outfits, and play a critical role in the market and in accelerating the demand for reforestation (Pan et al. 2022). To adequately address the impacts of climate change and biodiversity loss, however, reforestation efforts will need to not only produce enough seedlings to meet the demand but ensure that the seedlings produced represent a diverse range of native species from genetically appropriate seed sources (Nef et al. 2021). Meeting this objective will require close collaboration among scientists, government agencies, nonprofit organizations, and the private sector to effectively address the existing challenges to the reforestation pipeline.

The Reforestation Pipeline Begins With Seeds

Most reforestation efforts in the United States begin with seeds. Meeting our growing reforestation needs will require a robust and scalable seed supply chain (figure 1). Through survey-derived data, Fargione et al. (2021) estimated that the average nursery seed inventory in the Western United States can only supply 4.9 and 2.2 years of conifer and hardwood seeds, respectively, for reforestation at current levels and is insufficient to support a twofold increase in annual seedling production needed to meet the proposed 2040 goals.

Estimating the quantity of seed required for a given seedling order is challenging and depends on several factors, such as seed purity and germination capacity, that can vary among species and seed lots (seed collections from a known origin). Production factors that influence the conversion of seeds to shippable seedlings must be considered as well. When accounting for these factors in container nursery production, the seeds required to produce a shippable seedling could vary from 1.1 to 6.0 seeds per seedling (Bonner and Karrfalt 2008, Griffis and Lippitt 2021). For bareroot production, seed requirements typically include up to 10 percent of additional losses. These estimates do not account for factors after outplanting, such as transplant shock, browse, and drought, which could substantially increase the quantity of seeds required for a given reforestation project. This article will highlight the challenges impacting tree-seed availability in the Western United States and suggest opportunities for securing and improving the seed supply in an era of climate change.

Planning for Seed Needs

Unlike the previous century, in which reforestation was primarily focused on ensuring a continuous supply of timber, current reforestation needs in the Western United States are increasingly driven by wildfires, insect damage, and other disturbances (Dumroese et al. 2019, Stevens-Rumann and Morgan 2019). Foresters are also increasingly recognizing the need to maintain appropriate genetic and species diversity in reforestation efforts (Nef et al. 2021). Because wildfires and other large-scale disturbances are harder to predict, however, current reforestation efforts often have insufficient long-term planning and coordination, which is exacerbated by limited and unpredictable funding. This uncertain timing and funding can have negative effects on species selection, genetic appropriateness, seed quality, cost, and ultimately reforestation outcomes.

Additionally, areas with reforestation potential span Federal, State, Tribal, and private lands, thereby making up a complex mosaic of funding structures and management goals. Proactive planning for seed needs

Figure 1. The tree-seed supply chain consists of six key elements. Each element has associated opportunities to strengthen them.

is critical to shift from a reactive to a strategic approach to reforestation. Given the jurisdictional complexity, we need to understand: (1) the current seed inventory across both public and private holdings, (2) who has access to this seed inventory, and (3) species- and seed zone-specific gaps in current and future seed needs across land ownerships. Cooperation between public and private entities is crucial to ensuring that these goals can be achieved.

Public and private entities generally do not publish their internal seed holdings, and this information is not readily available to those making the requests. This lack of transparency makes it difficult to identify and address species collection gaps across geographic and jurisdictional boundaries. In addition, the seeds held in Federal storage facilities are only available for Federal use or sale to other government agencies under special provisions (e.g., Granger-Thye Act of 1950). To reduce competition with private industry and nonprofits, seed sales to private entities are not allowed (Watrud et al. 2012). While these policies have merit, if the private sector seed holdings are insufficient, this can limit reforestation potential on non-Federal land.

A national tree-seed needs assessment is one way to obtain a snapshot of the seed inventory status and availability across public and private institutions (Fargione et al. 2021, Jalonen et al. 2018). For example, the National Academies of Sciences, Engineering, and Medicine recently completed an “Assessment of Native Seed Needs and Capacities” for native plant species, and a similar analysis could be conducted for trees (NASEM 2023). To be effective, however, this approach should be detailed enough to be readily operationalized. In addition to an initial assessment, ensuring long-term utility would require a voluntary, consistent, and standardized seed inventory database that compiles key information about seed holdings among various agencies and the private sector.

Procuring seeds for specific species or sources typically requires several years due to limitations in collection capacity and variability in seed quality and masting. Additionally, at least 1 year is then required for seedling production. Thus, it is essential to project and prioritize seed needs for areas that may be at high risk of natural regeneration failure and will likely need active reforestation. This prioritization can be done by combining information on natural regeneration probability with projections of high-severity fire (Davis et al. 2020). Furthermore, investment in decision-support tools that combine seed inventory across Federal, State, Tribal, and private entities with projections on where regeneration needs are likely to occur would allow collection efforts to allocate limited resources to the highest priority areas. In the short term, this could allow collectors to prioritize strategic collections in areas where seed availability may decline significantly due to repeated large-scale fire or insect outbreaks and other climate change-exacerbated disturbances. Furthermore, developing the tools to spatially quantify seed holdings across organizations will likely reduce the risk of overharvesting from populations that are sufficiently represented in the existing seed inventory (or identify alternative sites to reduce collection pressure) and will help with planning for future re-collection.

While the USDA Forest Service already plans to use climate projections and vulnerability analyses to inform plans for future reforestation needs (USDA Forest Service 2022), these efforts will primarily focus on national forests, targeting only part of the reforestation challenge. Thus, it will be imperative to establish and maintain close coordination with partners to identify seed inventory gaps and address current and future needs across land ownership jurisdictions. Collaboratives that work across Federal, State, Tribal, private, and nonprofit sectors, as well as the establishment of working agreements (e.g., memorandums of understanding [MOU], memorandums of agreement [MOA], or joint powers agreements), can be avenues to facilitate coordination among partners. Optimally, these efforts should be regional but in aggregate provide national coverage.

Seed Sourcing in a Changing Climate

Tree seedlings have narrower climatic tolerances than their conspecific adults (Dobrowski et al. 2015, Marsh et al. 2022), thus the climatic niche for regeneration is a better reflection of a population's potential future range than the requirements of adult trees. Understanding how species' ranges may expand or contract will be especially critical for forest restoration following wildfire in the coming decades (Stevens-Rumann and Morgan 2019). The highest risk of inaction is especially acute for areas on the trailing edges of species' ranges and for species with low genetic variation or dispersal potential (Erickson and Halford 2020).

Long-term field trials indicate that seedlings planted outside of their appropriate seed zones perform poorly in terms of growth, survival, and adaptability because of climatic differences between the seed source and planting site (Alberto et al. 2013, Leimu and Fischer 2008). Seed zones have helped land managers decide where seeds can be safely moved from their origin without increasing the risk of maladaptation for tree growth and survival. As climate conditions change, however, the use of current seed zones will increasingly prove inadequate because formerly safe seed movement may no longer match the future climate of the planting site (St. Clair et al. 2022). Additionally, the broadening objectives of reforestation away from timber production and toward ecological resilience and function mean that a wider array of species will need to be considered for reforestation, most of which do not have empirical seed zones or transfer guidelines currently available (Pike et al. 2020).

Because future climates are uncertain and a moving target, seed lots chosen for a particular outplanting site should be adapted to the near-term climates as well as potential future climates occurring within a tree's expected lifespan. Therefore, the adoption of dynamic seed-transfer zones by land managers is increasingly needed. Existing web-based mapping tools like the Seedlot Selection Tool (https://seedlotselectiontool.org/sst/) can be a starting point for exploring how to match seed lots with appropriate planting sites based on current and predicted climate-change projections across the landscape. Additional guidance regarding the selection of appropriate climate variables and transfer limits will be needed from land management agencies or landowners based on the mix of species used, management objectives, and organizational risk tolerance (for recommendations and examples, see St. Clair et al. 2022). Conversations about assisted migration have been ongoing in the United States, but no clear policy decisions have yet been made, despite already observable evidence of range shifts among some species (Monleon and Lintz 2015). This lack of policy is in contrast with Canada, where the British Columbia Ministry of Forests fully transitioned to a climate-based seed transfer system in 2022 that mandates the use of assisted migration to mitigate climate-change impacts.

Refining and expanding policies and management guidance, especially as deviations in climate from historic norms increase, will require more modeling and empirical research. Some efforts are already ongoing. For example, the USDA Forest Service has established operational seed-source trials to evaluate the performance of seedlings matched to future climates. These trials are being rolled into an Assisted Migration Network across California, Oregon, and Washington on multiple land ownerships. While assisted migration trials represent a significant financial investment (e.g., $23,400 to $39,000 per site over each trial's lifespan, including installation, maintenance, and monitoring; O'Neill 2022), they provide data needed to validate and adjust modeling predictions and gauge unintended risks prior to the large-scale establishment (Sáenz-Romero et al. 2021). Continuing to expand these efforts across a broader range of species and geographic areas will be needed to meet reforestation objectives beyond timber production. Costs can be reduced by carefully selecting sites and seed lots to match the desired climate range, establishing sites in recently harvested locations, and running collaborative projects spanning multiple jurisdictions (O'Neill 2022, Sáenz-Romero 2022). Additionally, opportunities to incorporate assisted population migration and range-expansion pilot trials, established in partnership with forest managers on post-wildfire sites that are unlikely to recover naturally, could be more widely utilized in building the necessary evidence base to inform management guidance.

Seed Collection and Procurement

Increasing seedling production will require expanding the national seed inventory through collections. As shown in figure 2, seeds can be collected from seed orchards (often referred to as "improved") or from the wild (often referred to as "woods run"). Seed orchards have two key advantages over wildland collection: (1) they aim to produce high-quality seeds with increased genetic potential, and (2) they allow for a more efficient and systematic collection of seeds. Seed orchards, however, have only been established for a small number of species and seed zones in relatively few geographic areas. Additionally, because the selection and breeding of parents from seed orchards historically focused on economically important timber traits or specific disease-resistance attributes, many

Figure 2. Methods commonly used for conifer cone collections in the Western United States include (a) seed orchard collection, (b) squirrel cache (or "ground") collections, (c) tree climbing, and (d) fell and pick. (Photos courtesy of Mast Reforestation)

orchards today may not prioritize genetic traits that could be critical for conserving ecological function and adaptive capacity as the effects of climate change intensify (e.g., drought and temperature tolerance, the timing of growth and reproduction, and other traits related to climate may be more important in the future than rapid growth or taper; Hänninen and Tanino 2011, Niinemets 2010, Rohde and Bhalerao 2007). Finally, due to reduced investments in tree improvement during the past several decades, many orchards have suffered and have reduced production capacity (Wheeler et al. 2015). While a need exists to better quantify the current and future potential of seed orchards to contribute to the reforestation seed supply, new orchards will take additional investment and will require at least a decade to produce seeds (Bonner and Karrfalt 2008, Puritch 1977). In addition, managing seed orchards will necessitate expertise and long-term maintenance to achieve desired seed production volumes and quality.

In the absence of adequate seed supply from seed orchards, particularly in the short term, reliance on harvesting seeds from the wild will need to increase. In the Western United States, according to a survey of Federal, State, Tribal, and private nurseries, annual collections supply approximately 45 percent of the current seed needs, with only about one-third of nurseries collecting more than 50 percent of their seed from the wild (Fargione et al. 2021). The authors estimated that if seed sourcing from orchards remains unchanged, wild seed collection would need to increase severalfold nationwide to meet proposed reforestation goals by 2040. For the Western United States, an estimated 8 to 45 billion seeds may be required to produce 7.5 billion seedlings (table 1).

Wildland tree-seed collection involves harvesting seeds (or cones) from natural stands. Collections are either carried out by land-management agencies and organizations themselves or contracted out. Techniques and methodologies used include collecting from caches on the ground after squirrel cutting, tree climbing, and collection from felled trees on active harvest or thinning operations. Collection methods depend on the species, reproductive phenology, objectives, region, and the size and skillset of collection crews (figure 2). Collections from squirrel caches are the simplest logistically and require fewer skills but provide low precision of seed source locations and may result in lower quality collections than other methods. Alternatively, tree climbing and collection from felled trees are more precise, but they require advanced skills and training or complex coordination with logging crews, respectively. A combination of all collection methods will likely be required to meet seed supply needs.

Numerous biological and logistical constraints make wildland seed collection complex and time consuming. In the spring of 2022, a tree-seed procurement workshop, the Tree Seed Summit (TSS 2022), was held in Yreka, CA. Organized by DroneSeed Company (now Mast Reforestation), a reforestation service provider, TSS 2022 brought together diverse industry representatives, including private individuals (28 percent), nursery or seed extractory operators (21 percent), Indigenous peoples (12 percent), government agency staff (10 percent), private sector staff (9 percent), foresters (8 percent), academics (6 percent), and nonprofit staff (6 percent), with the goal of identifying the key constraints in the tree-seed supply chain. Participants identified: (a) the lack of clarity around tree-seed demand, (b) limited capacity for scouting potential collection sites, (c) difficulty with permitting, (d) a limited professional labor pool, and (e) poor communication between collectors and seed buyers as the key bottlenecks in wildland seed collection in the Western United States (authors' observations).

Predicting Demand and Improving Precollection Scouting

Wildland seed collection can be complicated by the lack of clarity around seed demand. Seed maturation is affected by many environmental factors, such as temperature, moisture, nutrient availability, and disturbance (Bonner and Karrfalt 2008). Mast seeding, or the synchronized but intermittent production of large seed crops by a population of perennial plants (Kelly and Sork 2002), is exhibited by many western conifers and requires monitoring of stands across wide geographies to understand where, and for what species, mast events are likely to occur in any given year. These factors make predicting where and when to collect more challenging.

Typically, scouting requires the forester or other accountable party to locate potential populations that may be suitable to collect from each year, identify trees to collect from, and facilitate dialogue with the collection crew to ensure the crew is available when the crop is mature (figure 3). When scouting is not possible due to limited resources or conflicting priorities, the likelihood of collecting a quality seed crop is reduced and can result in collection crews traveling hundreds of miles to a site only to find that the crop is not suitable, is immature, or has dispersed. These scenarios can significantly strain relationships between foresters and collectors, who operate on thin margins, work seasonally, and need to plan their time accordingly to earn their living. Improving clarity around longer term seed collection through climate-informed and genetically appropriate seed needs forecasts can help collectors and foresters anticipate and plan around collection opportunities, reduce costs, and increase collection efficiency.

Permitting and Land Access to Streamline Collections

For seed collectors, collection on public land has historically been a significant source of wild-collected seeds. These collections were accommodated through individual or commercial (contract) permits. Today, permitting for contracted collections has declined, and most collections on Federal land are done by independent collectors who apply for individual permits at public lands district offices to collect small quantities of seed with basic tools and techniques. This approach is often not strategic, whereby collectors collect opportunistically (e.g., from squirrel caches, low branches along trails, and roadways), targeting only a small number of species, source trees, or elevation bands. While small, individual collections can help supplement regional seed inventory and create rural jobs, reliance on independent and uncoordinated collections can add logistical complexity to the supply chain, specifically by increasing the need for quality and origin verification, staging, and coordination in seed (or cone) transport as well as reducing extraction and seed-cleaning efficiency (Silvaseed 2022).

Coordinated collections by cooperating independent collectors or by professionally trained collection crews can result in more efficient and higher quality collections (Maxwell and Aldhous 1967, Silvaseed 2022). The coordination of collectors requires a priori scouting and seed-quality assessment and may be particularly beneficial in years with significant masting when a supply line from scouting to collecting to transport can be built around the increased seed availability. In addition, coordinated seed collections can increase verifiable provenance data, improve logistical efficiency, and reduce costs. Modern geospatial tools can further enhance the efficient tracking of seed collections and inventory management in real time.

Increasing coordinated collection efforts will require streamlining the permitting processes, which can vary widely across agencies and can take several months or longer. Clear guidance and an efficient process are needed for contract collection permitting on Federal land. Furthermore, collection permitting to support landscape-level collections through cross-agency agreements (e.g., MOUs, MOAs, or Good Neighbor Authority agreements) is needed. For example, in 2022, Silvaseed Company and DroneSeed (now Mast

Reforestation) initiated a framework for a public-private MOU for commercial permitting for cone collection (Silvaseed 2022). By granting permission to collect on public land in Montana, U.S. Department of the Interior, Bureau of Land Management and the Montana Department of Natural Resources and Conservation enabled rapid, large-scale collections to improve access to seed collection to meet agency and private landowner needs throughout the State. Similarly, multi-ownership, landscape-level collection efforts are being initiated and coordinated through the New Mexico Reforestation Center (NMRC), which was founded in 2022 as a collaboration between the New Mexico Forestry Division, New Mexico State University's John T. Harrington Forestry Research Center, the University of New Mexico's Department of Biology, and New Mexico Highlands University's Department of Forestry. The mission of the NMRC is to meet the current and future reforestation needs of New Mexico and the greater Southwest, regardless of ownership, including facilitating access and permitting for seed collection (Sloan 2022).

Collection Labor, Training, and Communication

Most contracted tree-seed collections today rely on a sparse and aging cohort of professionals (Mendel 2021). Seed collectors must be knowledgeable about plant phenology and botany to know where and when to collect and often need to be trained arborists (or supported by arborists) to climb trees and obtain the highest quality seeds. Besides the technical and physical skills, successful collectors need to manage teams and inventory. Besides seed collectors, foresters contracting the collection should typically contribute to scouting collection sites, and thus also need to understand tree reproductive phenology, especially those characteristics associated with seed maturity and seed quality. Similarly, seed (or cone) transport crews, seed extractory staff, and nursery growers should all be well versed in seed biology to ensure that maximum seed quality is preserved through the seed supply chain. A cursory review of forestry programs accredited by the Society of American Foresters suggests that these topics are only briefly addressed in most university programs in the United States, making appropriate training and skills hard to acquire (authors' observations).

At TSS 2022, participants (n = 63) identified training, education, access to programs, and opportunities for involvement as key areas that need improvement. Expanding hands-on training through university courses, continuing education, and workforce development programs is needed to ensure that the investment into seed collection results in viable and genetically appropriate seeds. Standardizing these opportunities and offering inroads through direct training can increase the labor pool, while small-scale collection or site scouting can also be accomplished through citizen-science programs.

Post-Collection Handling

Immediately following collection, cones or other seed-containing fruits need to be stored in cool, well-ventilated conditions and transported to an extractory for cleaning and processing as soon as possible (Bonner and Karrfalt 2008). Post-harvest handling requirements vary among different species and plant functional types. In the Western United States, conifer collection and cone processing make up a large portion of regional extractory efforts due to their ecological and economic value. Depending on the distance between the collection site and the processing facility, the transport time and cost can be substantial. Securing resources for proper handling, storage, and transport can also be a challenge, especially for large-scale collection efforts. Improper handling during and after collection can significantly decrease seed quality. Thus, it is critical to ensure seed collectors and extractory staff are familiar with the appropriate handling requirements and can ensure these conditions.

Seed Cleaning, Processing, and Storage

Proper cleaning and storage are critical to maximizing the lifespan and quality of every seed lot (Bonner and Karrfalt 2008). Seed cleaning requires specialized equipment, an understanding of seed biology across many taxa, and hands-on expertise. For conifers, seeds are first extracted from cones using heat and tumbling. After extraction, a variety of processes remove inert plant material and de-wing the seeds to increase seed lot purity and quality. Seed storage requirements vary by species and region, but most western temperate species can be stored at stable, low moisture and temperature conditions for many years without notable loss of viability (see Bonner and Karrfalt 2008, Griffis and Lippitt 2021).

Historically, most Federal and State tree-seed cleaning facilities were operated as part of a national network of forest nurseries. Due to a series of budget cuts to Federal and State forestry programs and the decline of the timber industry since the early 1990s, the number of States with nurseries and operational seed extractories has declined by 19 percent since 2005 (Dumroese et al. 2005, NASF 2016). These declines have led to an associated reduction in seed storage and processing facilities, and the expertise needed to operate them. Most remaining agency-run seed facilities in the Western United States currently process modest tree-seed volumes. Limited staff and historic financial constraints may make it difficult for these facilities to increase processing capacity quickly (authors' observations). This could significantly limit the ability to meet proposed national reforestation goals. Therefore, an assessment of current seed processing and storage capacity and the potential for capacity expansion followed by strategic investment in infrastructure and training is likely warranted, particularly in regions with the greatest reforestation needs.

Finally, although the contraction in capacity following the decline of the timber industry also affected private-sector nurseries and extractories, many have maintained collection or cleaning facilities and may be able to scale seed collection and processing more rapidly than the public sector (authors' observations). Collaboration or contracting with the private sector could help offset agency capacity limitations and help serve the needs of myriad stakeholders, specifically underserved nonindustrial private forest landowners.

Seed Testing and Certification

Poor-quality seeds will have lower germination and vigor, produce a less robust nursery crop, and may lower seedling success (Finch-Savage and Bassel 2016, Rajjou et al. 2012). Seed quality is influenced by environmental factors during seed set, handling during collection and cleaning, and storage conditions and duration (Bonner and Karrfalt 2008). Standard tests have long been established and used to assess seed quality. Initial testing following collection and periodic testing during storage should be conducted to monitor seed viability, especially in cases where seed storage conditions are variable or seed storage behavior is unknown. While many extractories conduct in-house testing, third-party testing by an accredited lab is advised, and sometimes required. Therefore, building a relationship with a credible seed testing lab can be important to ensure consistent and reliable test results.

Maintaining the identity of the seed lot through accurate record keeping, precise labeling, and tracking through the seed supply chain is critical to ensure that appropriate seeds are used for each reforestation site (detailed recommendations are available in Bonner and Karrfalt [2008] as well as Bureau of Land Management [2021]). Seed certification is an official approach that can guarantee the capture and tracking of critical seed lot information (Bonner and Karrfalt 2008) by ensuring that every seed lot is properly identified by species and collection origin and that it has been harvested, cleaned, stored, and sold in compliance with the official certification standards of the legally appointed State certification agencies (Wolff 1981). Certification is particularly useful for international sales or when seeds are bought and sold among many parties, which can be the case in the private sector.

Currently, certification is not widely used in the Western United States for tree seeds (Aghai 2022). In the public sector, the lack of certification primarily occurs because agencies often have close oversight over collections and seed is not sold on the open market; in the private sector, certification costs can be a deterrent. The use of geospatial tools, combined with coordinated and strategic collections, however, can facilitate a more efficient and comprehensive certification process by reducing the cost of collection verification. Regardless of whether official certification is undertaken, seed lot information (e.g., species name, collection location coordinates, elevation, seed zone, date, number of individuals collected from, population size, and other relevant information) should be recorded for each collection and tracked throughout the seed supply chain.

Access and Distribution

Federal seed reserves are designated for use by Federal nurseries for the reforestation of Federal land. Non-Federal landowners and forest managers typically must work through State or public-private partnerships to gain access to seed for reforestation projects, if access is possible at all. This process is often complex, slow, and unreliable for non-Federal entities engaged in the reforestation of non-Federal lands (authors' observations). Because reforestation opportunities on private land represent approximately half of the total United States reforestation potential (American Forests 2021), increased and simplified access to genetically appropriate plant materials for these stakeholders is needed. Private companies and nonprofits working in the reforestation sector may be able to fill this gap.

Funding, Communication, and Collaboration

Seed collection, processing, storage, and transportation require a robust labor force and investment. Even at current production levels, labor shortages due to insufficient training opportunities, remote facility locations, and immigration policies that limit seasonal migrant worker availability have been identified as the single largest issue impacting the reforestation pipeline (Fargione et al. 2021, Westerman 2020). Addressing labor shortages through expanding educational and workforce development opportunities for rural communities and policies that increase pay equity and the availability of seasonal labor will be needed to meet the growing reforestation goals. Additionally, public-private partnerships can help bolster investment through structuring shared funding and land access to support the multiyear nature of seed sourcing and seedling production.

The forest tree-seed supply chain currently consists of a diversity of stakeholders, jurisdictions, policies, and financial mechanisms, which make up a complex matrix of communication needs (figure 3). Strengthening relationships among stakeholders across the seed supply chain, from seed collectors to seed extractories and nurseries to regeneration foresters, can build communication feedback loops through the entire reforestation pipeline, enabling learning and continual improvement (Fargione et al. 2021, Landis 2011).

Conclusions

A reliable supply of ecologically and genetically appropriate seeds is critical to ensure that nationally proposed reforestation goals can be met in the next few decades (Fargione et al. 2021). The current seed supply is insufficient, however, to meet the projected

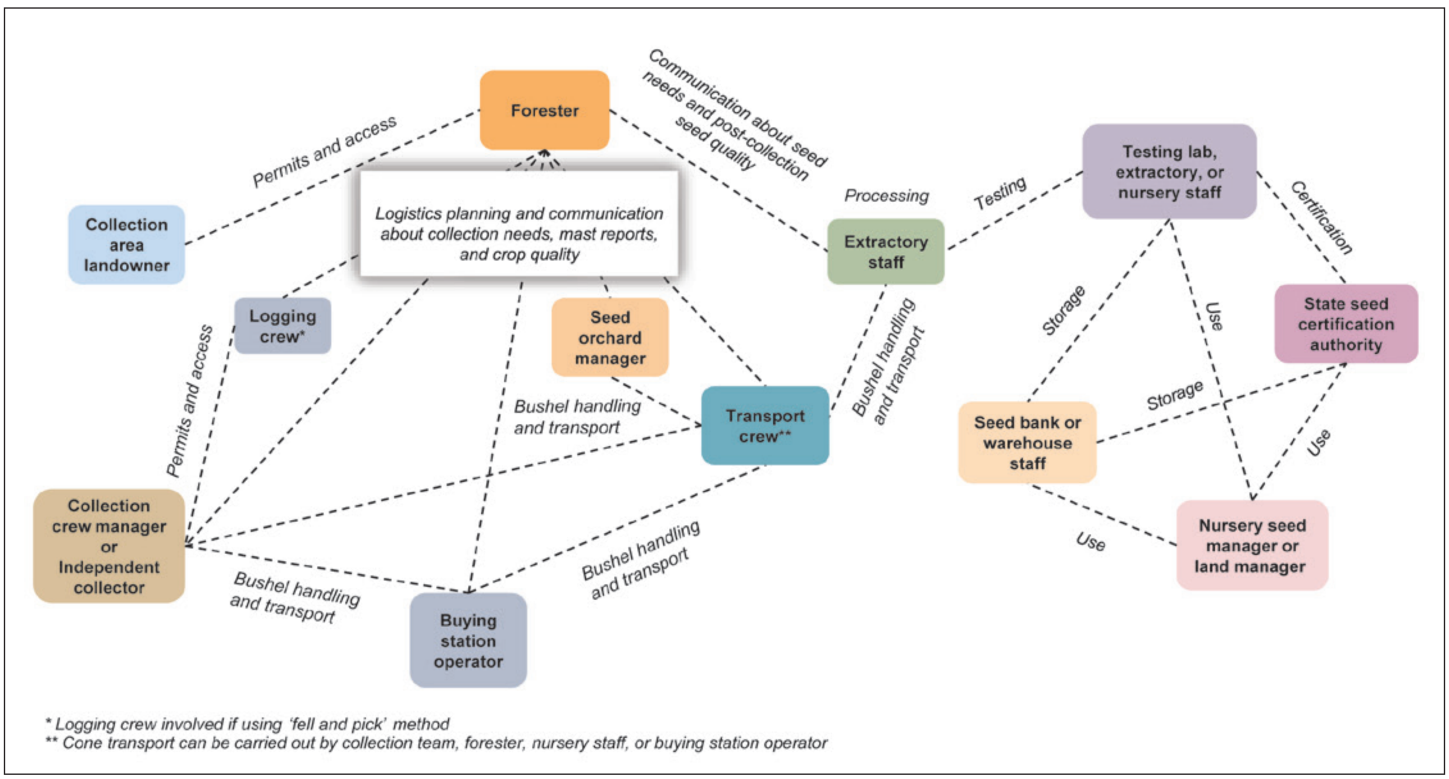

Figure 3. Stakeholder interactions along the tree-seed supply chain are critical to ensure efficiency and success. Boxes represent different stakeholders, dashed lines indicate communication or coordination needs between them, and line labels correspond to the processes or actions involved.

seed needs and could pose a significant bottleneck to the reforestation pipeline and thereby limit the capacity to maintain the Nation's natural resources and heritage. Increases in available Federal, State, and private sector funding and coordination present an opportunity to address bottlenecks and ensure a strategic and science-based approach to increasing seed supply. Such an effort could include the following actions:

- Conduct a national assessment of forest tree-seed inventory across jurisdictional boundaries.
- Compile a publicly accessible shared database and identify gaps in the national seed inventory.
- Prioritize strategic collections based on climate-change impacts and species or population vulnerabilities.
- Improve seed orchard production capacity and scope.
- Assess capacity and investment into seed collection, cleaning, and storage infrastructure and training.
- Establish coordinated funding, labor, resources, and access to reforestation plant materials across jurisdictions.
- Ensure communication feedback loops along the entire reforestation pipeline.

The USDA Forest Service has begun some of this work already as outlined in the National Forest System Reforestation Strategy (USDA Forest Service 2022). Federal agencies, however, represent only part of the reforestation potential across the Western United States. Therefore, timely engagement and partnership across State, private, and Tribal entities will likely be critical in ensuring that ecological integrity, function, and viability are incorporated into meeting seed supply needs across all land ownerships.

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Feedback Loops Support the Integral Role of Nurseries in the Reforestation Pipeline

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Abstract

Often overlooked, reforestation nurseries are now in the spotlight to meet increasing demands for tree planting. Improved efficiencies and expanded capacities are needed to meet increased seedling demand for the next decade and beyond. As an integral part of the reforestation pipeline, nurseries must coordinate their efforts with all other phases of the pipeline. Feedback loops to optimize seedling success are critical. First, nurseries must work closely with seed suppliers to maximize seed-use efficiency. Second, nurseries must focus within to address labor shortages by directing resources toward attracting and maintaining a skilled and effective workforce. Finally, nurseries must work with land managers to evaluate existing and new technologies to produce high-quality seedlings that will perform well in the field. The Target Plant Concept provides a continuous improvement framework to guide the feedback loops among seed, nursery, and field professionals. This paper was presented at The Reforestation Pipeline in the Western United States–Joint Annual Meeting of the Western Forest and Conservation Nursery Association, the Intertribal Nursery Council, and the Intermountain Container Seedling Growers Association (Missoula, MT, September 27–29, 2022).

Introduction

In a landmark paper evaluating the current status of reforestation and restoration, Fargione et al. (2021) underscored the need to fund, support, and expand all aspects of the reforestation pipeline, including seed collection, seedling production, workforce development, and pre- and post-planting practices to meet increased replanting goals. Nurseries form an integral part of the pipeline and are a focus of recently approved congressional funding via the Repairing Existing Public Land by Adding Necessary Trees (REPLANT) Act and executive funding through the Bipartisan Infrastructure Law (U.S. Department of Agriculture 2022). The legislation provides substantial funding to support reforestation efforts. Such resources occur perhaps once in a generation (Brown 2022). This funding presents an opportunity to reexamine the role that nurseries play in the overall success of reforestation and restoration programs.

To best achieve increased seedling production efficiencies and capacity, nursery professionals should visualize their role in the pipeline not as a straight line where production starts and ends at the nursery gate but rather as a series of feedback loops (figure 1). This article describes interactions and feedback between nursery professionals and seed suppliers within the nursery workforce itself and with land managers involved in outplanting and post-planting activities. Close collaboration regarding all aspects of the pipeline is required to meet the ambitious replanting goals set forth.

The Seed Supplier and Nursery Feedback Loop to Improve Seed-Use Efficiency

Seed is an increasingly valuable, and often limited, resource. Current retail value of the Washington Department of Natural Resources (WADNR) seed bank is approximately $9 million USD. This inventory has taken decades to develop through orchard breeding, woods-run collection, cone processing, seed cleaning and testing, and appropriate storage. The replacement cost is considerably higher than the current value (deGraan 2022).

In the vertically integrated reforestation program at WADNR, an inevitable tension exists between seed supplier and nursery manager. The seed supplier wants to maximize seed-use efficiency from each seed bank withdrawal. The nursery manager understands the value of seed but must also consider full occupancy of

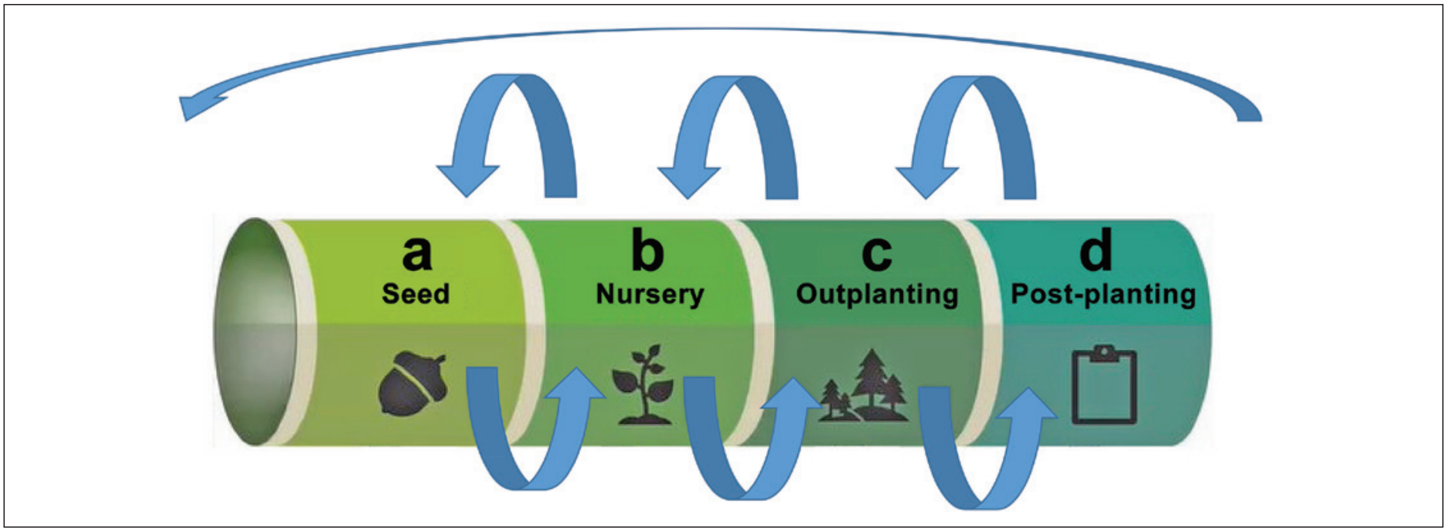


Figure 1. The reforestation pipeline can be thought of as a series of feedback loops for process improvement. This paper describes interactions of nursery professionals (a) with seed producers, (b) within the nursery workforce itself, and (c and d) with land managers involved in outplanting and post-planting activities. (Adapted from Fargione et al. 2021)

limited and expensive space in the facility. Ideally, a feedback loop exists between seed supplier and nursery manager (figure 2). The seed supplier strives to provide seed with high germination and purity, verified by regular retesting. The nursery requests an appropriate volume of seed and uses that seed efficiently. The end of the sowing season and completion of seedling packout provide opportunities for the nursery and seed supplier to review these efficiencies based on species or seed lot for future guidance. The following four sections describe scenarios where communication between nursery and seed supplier can improve seed-use efficiency.

Scenario #1: Only Low-Germination Capacity Seed Is Available

A grower considers several factors in determining how much seed to request. These factors include the germination capacity of the seed lot and associated confidence in that number based on age of the most recent germination test and past experience with the seed lot. When only seed with low germination capacity seed is available, a nursery will often over request to meet orders while reducing unused space. Growers typically request one additional seed per cell based on each 13-percent drop in germination

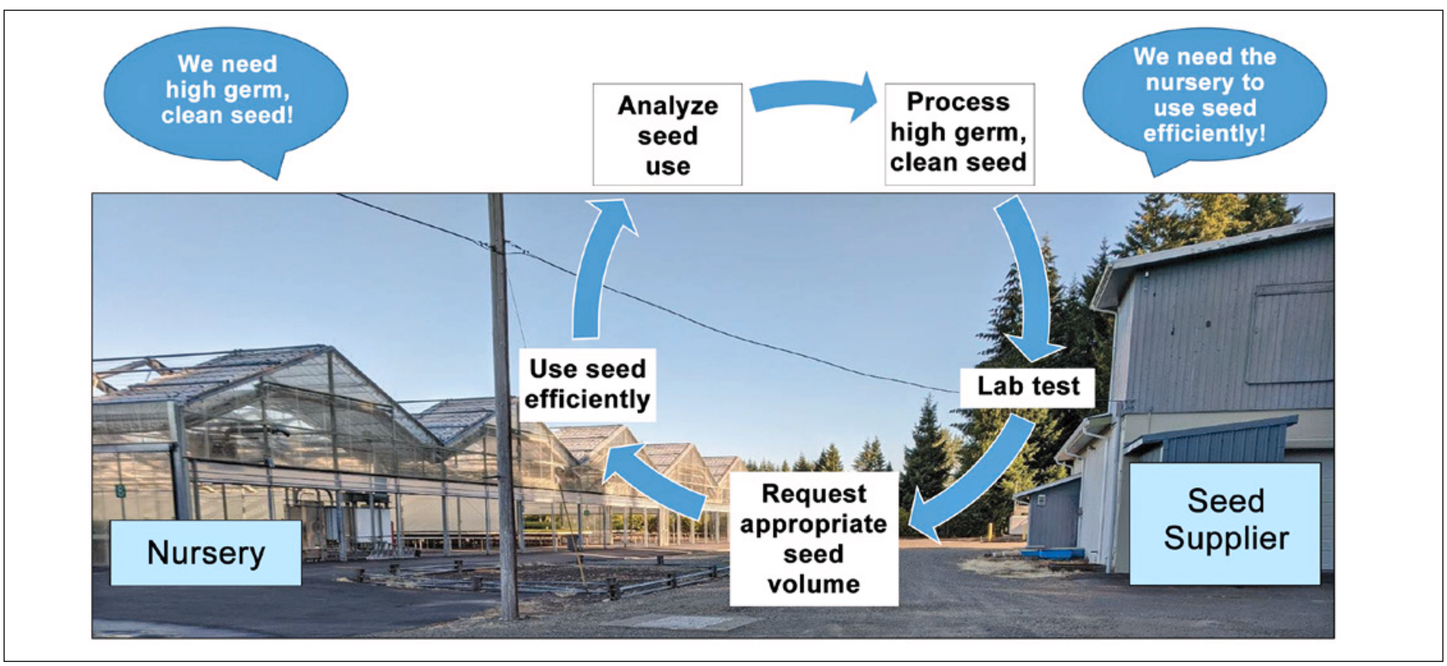


Figure 2. Clear and sustained feedback between the seed supplier and the nursery leads to improved seed-use efficiency. (Photo by Nabil Khadduri, 2022)

capacity to avoid empty cells and therefore unused greenhouse space (Kolotelo et al. 2001). For example, a grower may sow two seeds per cell of a lot with 90-percent germination capacity, increase that to three seeds per cell at 77-percent germination capacity, and double that to four seeds per cell if germination capacity is 64 percent. Since seed usage rapidly increases with decreasing germination capacity, a seed supplier/owner may conserve both labor and resources by taking steps to high grade low-germination or declining lots. Where high grading is not possible, a seed supplier can flag the lots in question for sowing in small containers, bareroot fields, or open compounds where space is less of a premium.

Scenario #2: Seed Is Only Available in Limited Supply or Is of Very High Value

In cases of limited and/or high-value seed, the seed supplier may suggest a contract between nursery and customer to cover the expense of single sowing. Nursery and customer should explore the following questions when determining the seed request: How valuable is the greenhouse space? What are the capabilities of the sowing equipment to conserve seed? How confident is the grower in meeting yield targets based on their skill, the species being grown, and the seed lot history?

Yield targets are typically 110 to 125 percent of the order amount to account for falldown during the growing process and still fulfill 100 percent of the order. Typically, 10 to 25 percent is the minimum oversow, but this will increase based on expected empty cells which, by definition, will not produce a viable seedling. To account for additional empty cells based on single sowing, communication and planning between seed supplier, nursery, and customer can conserve these seed lots.

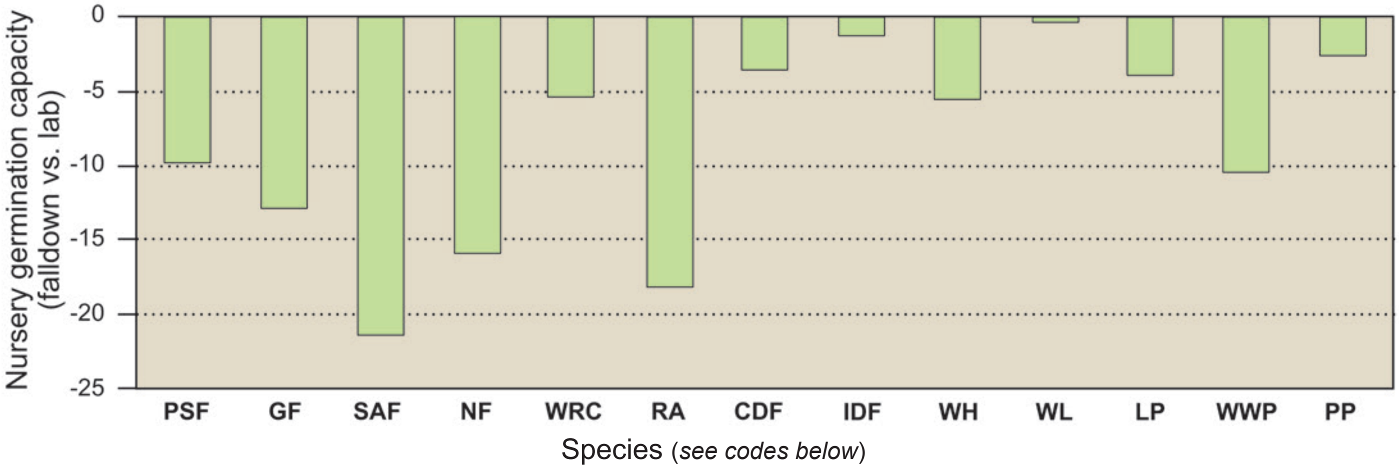
Scenario #3: Discrepancies Exist Between Seed-Supplier Germination Capacity Tests and Actual Germination in the Nursery

Lab data and actual greenhouse germination capacity can differ for various reasons. The lab is a controlled environment with standard germination conditions of 8-h light/16-h dark intervals at 30 °C (86 °F)/20 °C (68 °F), respectively. Labs standardize testing for year-to-year internal comparisons as well as comparisons across labs. The only pathogens present in the lab test will be seedborne in nature. Lab germination for most species is defined as extension of the radicle four times the length of the seed coat. Tests are replicated with 4 samples of 100 seeds evaluated to capture some measure of variability from test to test (ISTA 2022).

While greenhouses offer more control than bareroot environments, fully automated structures can still only be considered semi-controlled environments. Invariably, even the most advanced greenhouses will experience more variation in temperature and moisture compared with a lab setting. In addition to seedborne pathogens, other pressures may arise in the nursery. Despite best efforts to maintain a clean environment, additional pathogens from hard surfaces such as floors, walls, containers, equipment, and soil or growing media can infect seeds. Additionally, seed predation by animals, particularly birds, can occur. A grower defines germination much further along in the developmental stage than the lab test: when the seedling has fully emerged above the soil or growing medium. Additional time to reach the definition of nursery germination means additional opportunities for pathogens and pests to affect germination. Further delay of greenhouse germination can occur due to inconsistencies in top dressing, particularly excessive application over the seed. Finally, nursery germination tracking tends to involve smaller sample sizes than lab evaluations or does not use replication to account for variability.

Germination capacity across several western Canada and Pacific Northwest species shows that true firs (*Abies* Mill.), red alder (*Alnus rubra* Bong.), and western white pine (*Pinus monticola* Douglas ex D. Don) stand out as particularly susceptible to nursery germination capacity falldown compared with lab tests (figure 3) (Kolotelo 2021).

Fortunately, there are several seed treatments that a grower can use to close the gap between lab and nursery germination performance. Nurseries apply seed sanitation to reduce fungal pathogen loads on the seed. Growers can also manage moisture content after seed imbibition by surface drying seeds so that the necessary moisture to release dormancy is on the inside of the seed, rather than on the outside of the seed where it might lead to pathogen buildup. Surface drying seed allows the grower to extend stratification beyond general lab prescriptions. Operational germination



Species	Common name	Scientific name
PSF	Pacific silver fir	*Abies amabilis* (Douglas ex Loudon) Douglas ex Forbes
GF	Grand fir	*Abies grandis* (Douglas ex D. Don) Lindl.
SAF	Subalpine fir	*Abies lasiocarpa* (Hook.) Nutt.
NF	Noble fir	*Abies procera* Rehder
WRC	Western redcedar	*Thuja plicata* Donn ex D. Don
RA	Red alder	*Alnus rubra* Bong.
CDF	Coastal Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
IDF	Interior Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.)
WH	Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
WL	Western larch	*Larix occidentalis* Nutt.
LP	Lodgepole pine	*Pinus contorta* Douglas ex Loudon
WWP	Western white pine	*Pinus monticola* Douglas ex D. Don
PP	Ponderosa pine	*Pinus ponderosa* Lawson & C. Lawson var. *scopulorum* Engelm.

Figure 3. Discrepancies often occur in germination capacity between the lab and nursery for several western Canada and Pacific Northwest species. Data from British Columbia Ministry of Forests Tree Seed Centre and cooperating nurseries, 2015–2020 (Kolotelo 2021).

temperatures are generally lower and more variable than lab temperatures. Extending stratification releases seed dormancy more completely and allows seed lots to uniformly approach full germination capacity despite varied environmental conditions. In some cases, delayed dryback or "surface wet-surface dry" stratification is appropriate, such as with many true firs and western white pine. In this case, seeds may be kept in a surface-wet condition for the first 4 weeks of chilling, followed by surface drying to reduce the risk of pathogen development during the remaining weeks to months of stratification. Differences in seed weight between live and dead seed at this midpoint of stratification or at the end of stratification also present an opportunity to high grade seed.

Growers often maintain relatively warm greenhouse temperatures during germination to shorten the time to germination. Accelerating germination with heat produces a uniform crop while also reducing exposure to pathogen attack and animal predation but comes at an energy cost. To reduce this cost, some growers use a thermal priming technique by prewarming seed in a smaller space that is cheaper to heat while still providing adequate heat units to accelerate germination. For more in-depth descriptions of the above techniques, see Khadduri (2021).

In practice, most growers extend stratification beyond a standard lab prescription (figure 4). Depending on species, many growers will use a delayed dryback during stratification, and a smaller percentage use mid-stratification high grading and thermal priming to improve seed performance. Ultimately, detailed and sustained germination feedback between seed supplier and nursery facilitates the justification of additional resources needed to carry out the treatments described above.

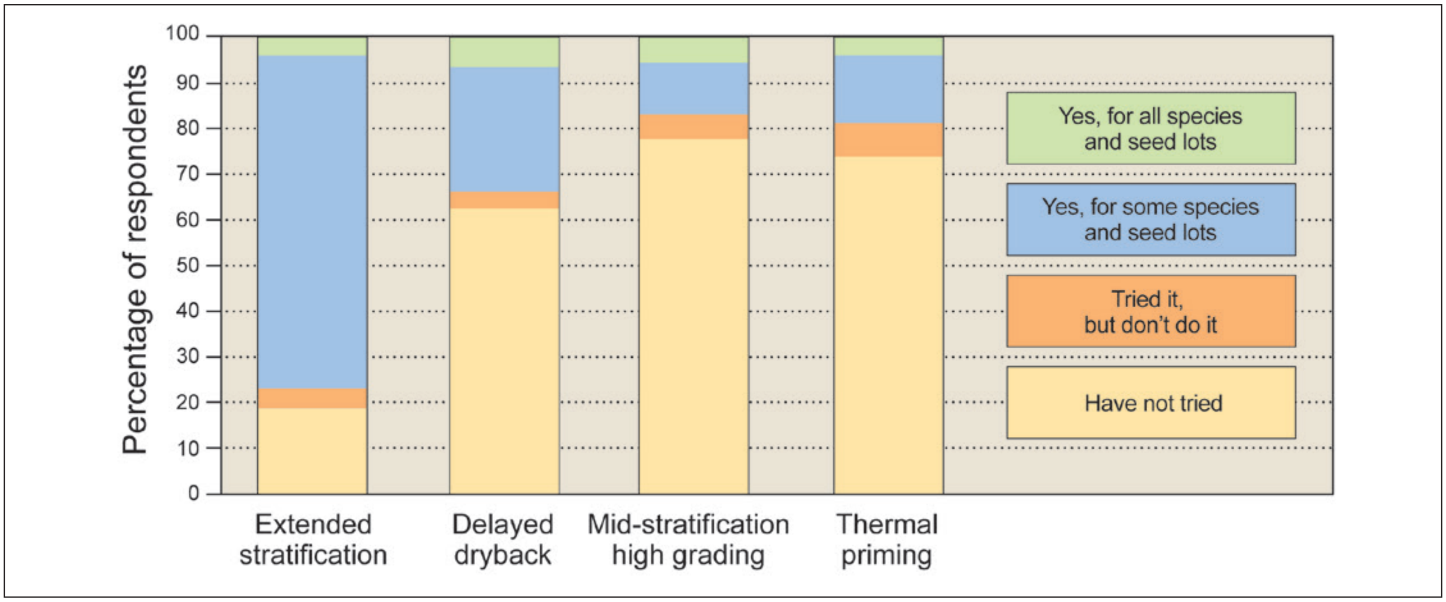


Figure 4. Respondents from the United States and Canada (n = 59) practice various seed germination techniques as surveyed in a 2020 live webinar poll (Khadduri, 2021).

Scenario #4: Sowing Equipment Value is Not in Line With Seed Value

Feedback between the seed and nursery programs within WADNR identified upgrades to sowing equipment as a critical priority to increase overall seed-use efficiency. With the increasing cost of seed and occasional seed scarcity, the latest automated seeders allow for more precise placement and distribution of seeds in containers in addition to increased speed (figure 5). While expensive, needle and vacuum sowers are particularly useful in fractional sowing. For example, advanced seeders can sow an average of 1.5 seeds per cell by evenly distributing cells with 1 or 2 seeds, saving considerable seed in the process.

Investing in modern sowing equipment can quickly pay for itself as the value of seed increases. This investment comes with two caveats for success. First, a nursery must communicate to the seed supplier that clean, high-purity seed is particularly important with automated seeders as machines will sow whatever material is in front of them (figure 6). Second,

Figure 5. Automated seeders, such as (a) the vacuum needle seeder and (b) the vacuum drum seeder, speed up sowing and increase sowing accuracy. While expensive, increased time savings and seed-use efficiency will quickly recoup costs. (Photos by Nabil Khadduri, 2022)

Figure 6. Clean, high-purity seed is important for automated sowing to ensure all cells are filled. Additional cleaning steps may be needed, such as pitch separation, to prevent equipment clogging. (Photo by Nabil Khadduri, 2021)

automated equipment will only be effective with a skilled and experienced operator who is able to finesse the machine to accomplish sowing objectives.

The Nursery Workforce Feedback Loop to Recruit and Retain Nursery Staff

Recruiting and maintaining a skilled workforce is increasingly challenging in many industries, and the reforestation community is no exception. Within WADNR, and anecdotally across many other forestry organizations, an "even-aged stand" retirement has occurred. Driven in part by the extraordinary events of 2020, organizations already weighted towards an older workforce experienced many people retiring within a 1- or 2-year period. Additionally, employment opportunities within and outside the reforestation community have led to increased shifts in the workforce.

To build and maintain a skilled workforce, the reforestation community must consider three strategies. First, increase pay to keep up with the rising tide of salaries and inflation. Second, identify and invest in young talent through competitive internship programs that pay a reasonable salary and provide a housing stipend where appropriate. Third, reward and retain existing employees through continuing education and promotion opportunities.

Money Talks: Recruiting Through Pay

Many people gravitate to the reforestation industry because they enjoy the tangible results of hard work in the outdoors and feel good about contributing to environmental well-being. Nevertheless, employees also pursue salary and benefits. Positions must be competitive both within and outside the industry. Inflation has increased by 29 percent during the last 10 years (U.S. Bureau of Labor and Statistics 2022) (figure 7). The average cost of a seedling at the

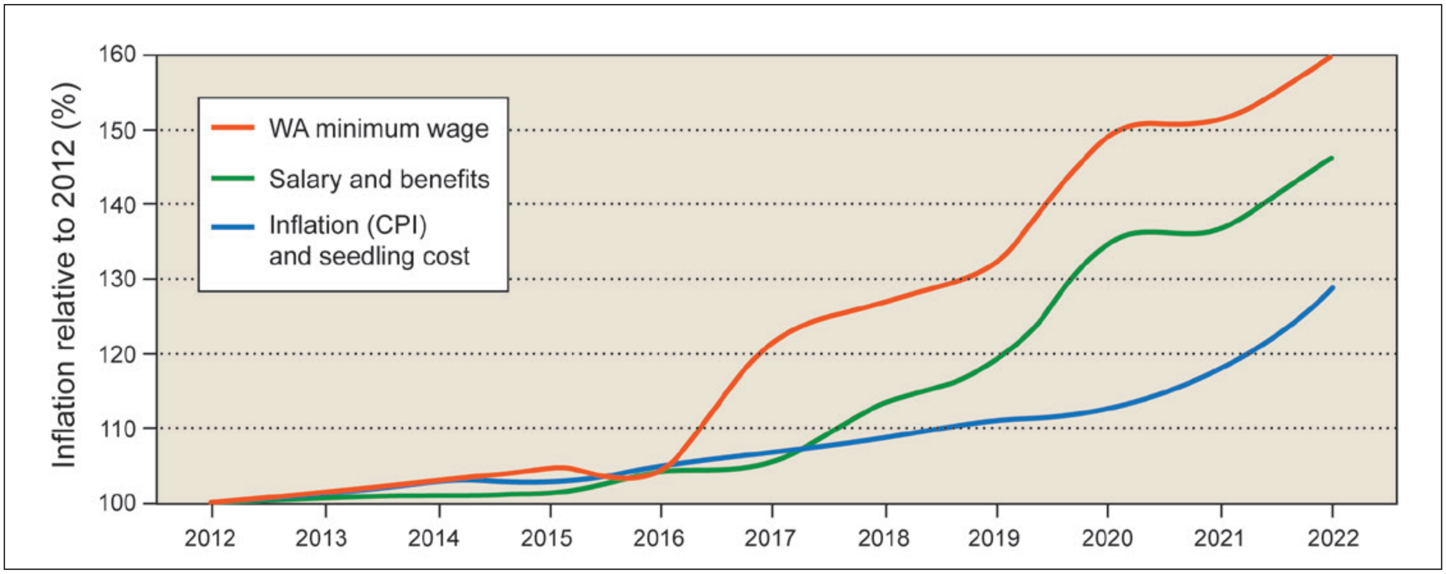


Figure 7. At the WADNR Webster Nursery, seedling prices have risen with inflation (Consumer Price Index [CPI]) over the past 10 years. Nursery salary and benefits have risen comparatively faster, especially over the past 5 years. This increase is driven in part by a steady increase in the Washington State (WA) minimum salary wage.

WADNR Webster Nursery increased by 31 percent in the same time period, roughly keeping pace with inflation. To attract and retain staff during that time, salary and benefits increased by 46 percent (figure 7). This increase may be due in part to upward pressure resulting from a 61-percent increase in Washington State's minimum wage. The University of Idaho Pitkin Nursery, which operates in a different minimum wage structure, has increased salary and benefits 20 percent in the past 5 years to attract and retain employees (Nelson 2022). Ultimately, the increased discrepancy between nursery salary and benefits and current seedling prices means price hikes are unavoidable to keep nurseries solvent.

Recruiting Students Through Competitive Internship Programs

Recent retirements have emphasized the need for the reforestation industry to focus on building a pipeline of people. In a 2020 survey, workforce was identified as the top limiting factor to nursery production and expansion (Fargione et al. 2021). Only certain individuals in certain circumstances can afford unpaid internships and volunteer opportunities. These positions, however, are often the only opportunities available to students interested in reforestation. Internship programs need to be competitive and able to cast as wide a net as possible by providing reasonable hourly rates and housing stipends where appropriate. In the case of WADNR, executive funds have been allocated recently to fund internship programs across a range of agency work groups, thereby reducing the financial burden on any one individual working group and enabling better student recruitment.

During a panel of AmericanHort Scholars at the Cultivate '22 conference (Columbus, OH), Dr. Melinda Knuth noted, "The younger generation in today's workforce will be loyal to their employer, but they expect their employer to build a positive work environment and help them reach their goals. If you don't give them the same amount of energy, they will quit. It's a partnership and they will be loyal to you" (Hullett 2022).

Internships operate as extended interviews, giving the employer and the intern an opportunity to evaluate each other. More than ever in today's competitive hiring market, such an upfront investment into future employees can help ensure effective recruitment and long-term retention.

Rewarding and Retaining Employees Through Continuing Education Opportunities

Providing continuing education opportunities shows employees that their employer cares about their professional development. Applied education rewards motivated employees and provides them a pathway to career advancement. Following is a curated list of continuing education resources for the nursery industry, with a focus on greenhouse-related education.

- **Reforestation, Nurseries, and Genetic Resources (RNGR) website**

  Maintained by the U.S. Department of Agriculture, Forest Service RNGR program, this clearinghouse website (https://rngr.net) is accessed throughout the world and includes an abundance of resources for reforestation professionals (Haase et al. 2011). Users can download or order nursery manuals, search by topic or author for articles from the database of nearly 12,000 articles (including all past issues of Tree Planters' Notes), and learn about upcoming events. In addition, the site includes specific information on seed technology, Tribal resources, and tropical reforestation.

- **University of Florida and Michigan State University extension courses**

  The University of Florida's Institute of Food and Agricultural Sciences offers several online greenhouse training courses (https://hort.ifas.ufl.edu/training). Each of these extension courses costs $250 USD and requires 3 to 4 hours per week in an on-demand format. Course topics include an introduction to greenhouses, pest management, irrigation, and nursery administration. Many of the courses use the Back Pocket Grower resource (https://www.backpocketgrower.org). The program has partnered with Michigan State University extension greenhouse courses to also offer a plant health certificate (https://www.canr.msu.edu/online-college-of-knowledge/index).

- **University of Idaho associate degree program in Forest Nursery Management and Technology**

  Starting in fall 2023, this 2-year program will offer a range of courses to prepare people for a career in forest nurseries (https://www.uidaho.edu/cnr/center-for-forest-nursery-and-seedling-research). The courses will cover topics in career development, growing media, pest management, nursery management, and nursery design. The goal is to eventually make several courses available as non-credit extension classes in a hybrid format.

- **Publications and online resources**

  Many scientific and trade magazines provide extension and industry-supported articles relevant to methods, technologies, and trends in reforestation. These include Greenhouse Grower (https://www.greenhousegrower.com/), Growertalks (https://www.growertalks.com/), and e-Gro (Electronic Growers Resources Online; https://www.e-gro.org/), which is specifically supported by extension horticulturalists.

  Also, *Water, Root Media, and Nutrient Management for Greenhouse Crops* (Merhaut et al. 2018) is an excellent manual authored by 17 extension and industry professionals with applied, up-to-date knowledge on important aspects of greenhouse growing.

The Nursery and Land Manager Feedback Loop to Evaluate Existing and New Seedling Production Techniques

The Target Plant Concept (figure 8) provides a continuous improvement framework in which nurseries work with field professionals to evaluate seedling stock type performance and identify opportunities for increased survival and rapid establishment (Dumroese et al. 2016). By partnering with the silviculturist or restoration specialist, the nursery professional can better understand the challenges faced on the landscape and what attributes will make a seedling most fit for specific sites and goals. Defining and refining target plants at the outplanting site improves reforestation success and helps the land manager and nursery grower to understand that seedling quality, not appearance, dictates success.

The Value of Outplanting Trials

A well-designed and executed outplanting trial (Haase 2014) will provide meaningful answers about which reforestation practices work and which need improvement (figure 9). Together, the nursery and reforestation professional target morphological and physiological characteristics that can be quantitatively linked to outplanting success on specific sites. Next, well-designed trials to compare stock types, seed lots, nurseries, planting dates, or other factors are established to evaluate survival and growth performance. Feedback from these trials can then be used to improve production or outplanting practices for the future.

Pinto et al. (2011) describe some of the dangers of poorly designed stock type trials. It is important to keep seedling quality, seed sources (genetics), originating nursery, density, and culturing regimes the same within a trial unless one of those factors is the treatment to be evaluated. Avoid conducting single-year analyses as performance may change from year to year due to environmental variability. Where possible, supplement morphological measurements

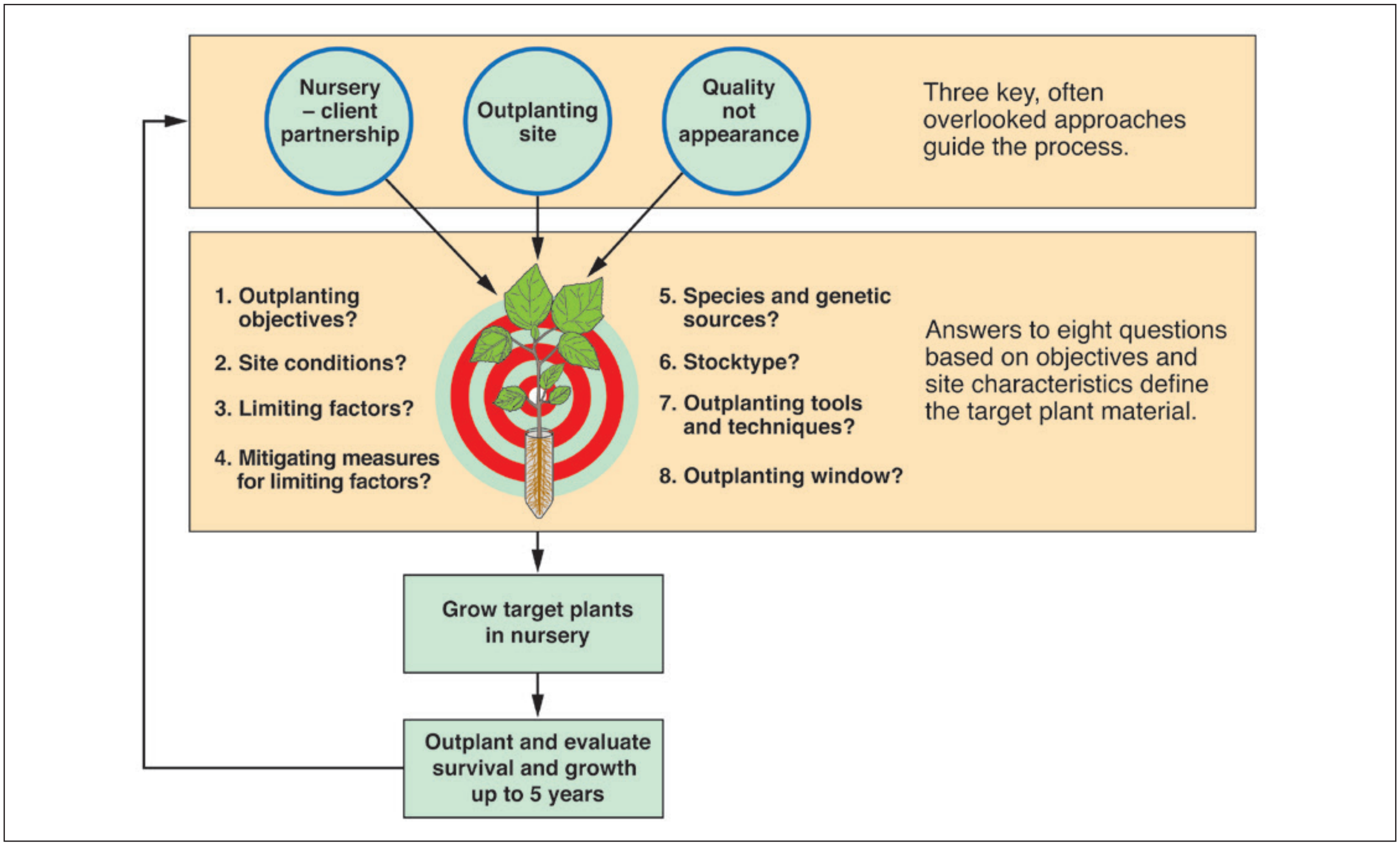


Figure 8. The Target Plant Concept is a holistic approach to reforestation that emphasizes communication between the nursery and land manager. This continuous improvement process identifies seedlings that are "fit for purpose" based on appropriate morphological and physiological characteristics matched to the outplanting site (from Dumroese et al. 2016).

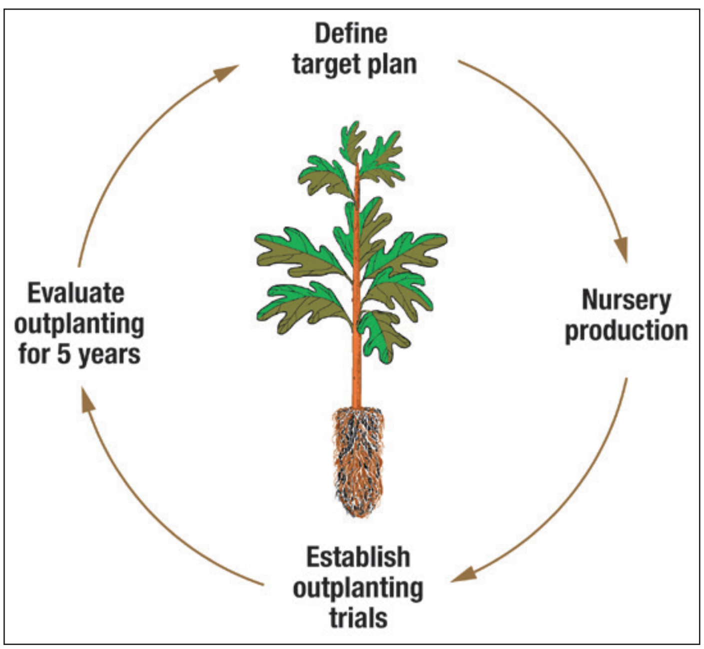


Figure 9. A well-designed and executed outplanting trial will provide meaningful answers to what works and what needs improvement (adapted from Pinto et al. 2011).

with physiological measurements to get a deeper understanding of differences that may or may not occur.

Conclusion

Nurseries are just one part of the reforestation pipeline, but their role is central to its success (Haase and Davis 2017). To operate efficiently, the pipeline should not be seen as a linear process consisting of separate parts with minimal interaction. Rather, feedback communication loops—between the seed supplier and the nursery, within the nursery itself, and between the nursery and the land manager—provide the best opportunity to refine and optimize the process. Forthcoming investments in nursery infrastructure are surely needed to meet increased seedling demands. In the end, lofty reforestation goals will only be met by also investing in people, including nursery staff eager to interact with, and learn from, other reforestation pipeline professionals.

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Outplanting Seedlings in the Pacific Northwest: Historical Efforts and Contemporary Constraints to Success

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Abstract

As incidence of wildfires increase across the Western United States and world leaders call for the implementation of tree-planting programs to mitigate the effects of climate change, the demand for tree seedlings has surpassed current nursery capacity. Reforestation goals cannot be met, however, by increasing nursery capacity alone. Outplanting capacity must be scaled simultaneously with increasing seedling production. Once seedlings leave the nursery to be outplanted, their survival is dependent on a number of factors, including expertly timed site preparation, storage and transport specifications, timing and logistics for seedling delivery, labor availability, planting method, and the interaction between the planting prescription and biophysical conditions onsite. Building a greater understanding of historical and current outplanting practices as a social framing of current outplanting capacity may be useful as the industry prepares for surges in financial resources for improving the reforestation pipeline. This article examines the components of the outplanting process based on literature reviews, interviews with foresters, planting crew foremen, planters, and field observations during planting events throughout the Pacific Northwest. Results indicate that current outplanting practices have changed very little in the last 80 years, yet planting outputs are increasingly expected to meet growing reforestation demands. Planters are limited by myriad species and stock types, tool types, and elevation ranges. To improve future outplanting operations, innovating in tools and equipment to reduce the burden of labor is critical, along with addressing the issue of sourcing and supporting future labor pools with the appropriate infrastructure to expand the outplanting pipeline. This paper was presented at The Reforestation Pipeline in the Western United States–Joint Annual Meeting of the Western Forest and Conservation Nursery Association, the Intertribal Nursery Council, and the Intermountain Container Seedling Growers Association (Missoula, MT, September 27–29, 2022).

Introduction

The demand for reforestation in the United States is growing. A recent national analysis found that 64 million acres of natural lands have the potential for artificial regeneration investment (Fargione et al. 2021). Of this, 25 million acres are in the Western United States with about 6.5 million acres in the Pacific Northwest (California, Idaho, Oregon, Washington). Reforestation programs are receiving increased Federal support via legislation such as the Repairing Existing Public Land by Adding Necessary Trees (REPLANT) Act, which expands funding towards reforestation on National Forest System (NFS) lands managed by the U.S. Department of Agriculture (USDA) Forest Service (United States Senate Committee on Agriculture, Nutrition, and Forestry 2021). The Biological the Infrastructure Investment and Jobs Act (IIJA) and Bipartisan Infrastructure Law (BIL) extend beyond NFS lands to increase funds for nursery and reforestation infrastructure needs on Tribal, State, and other public lands (Balloffet and Dumroese 2022, Parajuli 2022). In addition, the Inflation Reduction Act (IRA) increases the tree-planting budget for private and urban forestland (Federal Register 2022, Sustainable Forestry Initiative 2022). To meet the ambitious reforestation targets proposed by myriad scientists and political figures, and supported by the public, each component of the reforestation pipeline (i.e., seed, nurseries, outplanting, and post-planting care) must be thoroughly assessed and then proportionally improved (Fargione et al. 2021). Ultimately, the potency of the reforestation pipeline will be dependent on the collective ability to successfully address each of these components to meet current and future demands.

A Look Back

Historically, resources were invested into advancing outplanting capabilities in response to societal needs (e.g., wildfire recovery and employment programs of the early 1900s) and later in response to shifting forest management practices among the commercial forestry sector for plantation management (Taylor 1948). In the early 1900s, forest loss and ecosystem degradation were of paramount concern due to increasing occurrence of wildfires and largely unregulated timber harvesting. Artificial regeneration practices gained traction during the last century as landowners sought to exert more control of their forest resources (e.g., stand density, species, stock type, etc.) by growing and planting seedlings (Curtis et al. 2007, Taylor 1948). As a result, several nurseries were established that were either directly supporting the timber industry or producing tree seedlings for a combination of local horticultural and forestry needs. Large timber companies opened their own nurseries to have a supply of seedlings for more sustainable management of their timberlands. In addition, the USDA Forest Service established nurseries around the country including the Wind River Nursery (Washington), Monument Nursery (Colorado), and Savenac Nursery (Montana) in the Western United States (Curtis et al. 2007, Donoghue 1982, Dumroese et al. 2005).

Federal programs also supported mass reforestation efforts by establishing subsidized tree-planting operations. For example, one of the functions of the Civilian Conservation Corps (CCC) was to address forest-management concerns and curb unemployment caused by the Great Depression (Dumroese et al. 2005, Maher 2008, Otis et al. 1986, Paige 1985, Throop 1979). The CCC was comprised predominantly of young men incentivized with wages, benefits (e.g., free meals, lodging, medical care, and dental care), and support infrastructure (e.g., barracks, mess hall, bath house, classrooms, and hospital) (figure 1) (Paige 1985). The CCC and their planting operations functioned from 1933 to 1941 under a strict hierarchy reflective of the military chain of command and facilitated intensive labor that helped to meet the reforestation goals of the time (Paige 1985).

From the 1940s onward, forest nursery technology and the corresponding outplanting programs evolved to improve seedling quality and subsequent outplanting performance for a variety of planting environments using science-based approaches (Curtis et al. 2007, Haynes 2003, Sharp 1949). Nurseries worked to provide seedlings of known source with consistent materials and packing specifications using best management practices to meet seasonal demands across a diversity of ecosystems. With standardizations and stock type specifications, foresters grew more adept at prescribing the appropriate artificial regeneration strategy to a given outplanting site. The parallel maturation of these nursery and outplanting programs revealed an opportunity to further refine artificial regeneration by constructing formal processes for feedback loops and improvements. This process came to fruition with the introduction of the Target Seedling Concept (TSC) in 1990 to link seedling morphological and physiological quality with subsequent outplanting success (Rose et al. 1990). When applied to the reforestation pipeline, the TSC provides a feedback loop between nursery and client to accommodate varied ecoregions and multifaceted reforestation efforts (Dumroese et al. 2016).

Despite the significant advancements in nursery production and site preparation techniques to support outplanting efforts, the physical process for outplanting seedlings has largely remained the same, with improvements isolated to introductions of various tools such as the Pottiputki developed in Finland (BCC, Sweden) and the planting gun developed in Canada (Walters 1963). Otherwise, the most common planting tools are the planting shovel, planting hoe, planting bar, and dibble (table 1) (Elfritz et al. 2006, Haywood et al. 2013, Kloetzel 2004, Missoula Technology and Development Center 2013). Although tractors and other machinery (e.g., continuous furrow planters and intermittent planters) have been used for decades to outplant seedlings in the Great Plains and the Eastern United States (Barnett 1974, Stoeckeler and Slabaugh 1965), they are seldom used for reforestation in the Western States because of rocky soils, steep slopes, and remote locations. The long-term reliance on manual labor via tree planting

Figure 1. (a) Strictly organized planting by CCC crews resulted in high productivity on tree planting projects and other forest management responsibilities. In such a rigorous structure, crews were incentivized with support infrastructure, such as (b) barracks, (c) dining facilities, and classrooms. (Photos from Museum of North Idaho: CCC-7-37, FS-13-033, CCC-4-10)

crews for outplanting tree seedlings in the Western United States has also been influenced by associated costs, such as equipment, seed, seedlings, transportation, lodging, etc. (Dumroese et al. 2016, Granzow et al. 2018, Kloetzel 2004).

Current Practices

Today, the confluence of climate-driven disturbance events (i.e., increased wildfire risk, drought, and altered precipitation patterns) and legislation to support healthy and resilient forests is once again driving innovations in forest management practices, such as reforestation, through an unprecedented expansion of tree planting efforts (Fargione et al. 2021, Grossnickle and MacDonald 2021, Keenan 2015, Parks and Abatzoglou 2020). To approach the backlog of acreage in the country that requires reforestation and to reach reforestation targets proposed by Fargione et al. (2021), seedling production in the United States must increase from its current estimated national production of approximately 1.4 billion seedlings annually (Haase et al. 2022) to approximately 4 billion seedlings annually. This expansion in seedling production justifies the provision for increased capacity and innovation of outplanting practices. To achieve these targets requires addressing labor shortages, seasonal shifts in planting and sowing timelines, and lackluster or outdated nursery and planting infrastructure (Grossnickle and MacDonald 2021).

Implementing the new, proposed planting regimes will be challenging. Labor shortages are the single greatest challenge that must be overcome to meet current reforestation goals (Fargione et al. 2021, Trobaugh 2018). Currently, approximately 82 percent of the forestry industry's labor force consists of temporary H-2B-certified employees (Bier 2021)

Table 1. Description and utility of historical and current tools used in seedling outplanting.

				
Tools	Hoedad, Rindt, Mattock, Narrow Blade (plug), Swedish, Wifsta	OST Bar, KBC Bar, Planting Spear	Planting Shovel, Round-point Shovel, Garden Shovel	Dibble Bar
Average cost	$45	$25–35	$20–25	$46–66
Planting rate (trees per day)	800–1,000	350–400	24–350	160–2,000
Stock type(s)	Bareroot and container	Bareroot and container	Bareroot and container, larger seedlings	Small bareroot and container
Weight range (lbs)	3.0–7.5	8.0–10.0	~2.0–7.0	~8.0
Planting utilities	• Used for scalping and creating planting holes • Varied blade angles, 90 to 100˚, depending on slope and site conditions • Lightweight, tough, easy to handle • Versatile and inexpensive • Effective in steep terrain, rocky or clay soils, heavy brush, or slash	• Common tool for planting in hard, rocky soils with roots • Simple, inexpensive, and versatile • Less fatigue on operators • Used in confined spaces, on steep slopes, or rocky ground	• Produces large planting holes primarily for seedlings with large root systems • Ability to maximize soil displacement • Easy use for inexperienced planters • Well suited for planting in areas where high survival rates are crucial • Most effective in deep, loose soils	• Fast hand tool • Creates small holes • Effective in loose soils

Table 1 continued on next page

Table 1 ***continued.*** Description and utility of historical and current tools used in seedling outplanting.

				
Tools	Hand auger, power auger	Hammer-action hand planter	Adze hoes, duty scalping tool, American eye hoe, Pulaski, McLeod, Pickmattock	Pottiputki
Average cost	$600–2,000	$675–1,000	$20–30	$255-265
Planting rate (trees per day)	400–750	280–480	80	N/A
Stock type(s)	Bareroot (including large sizes) and container	Bareroot and container	Container, including large sizes	Container
Weight range (lbs)	~7.0–14.0	11.0 –22.0	~3.0–7.5	~5.5–8.0
Planting utilities	• Creates holes for large seedlings • Beneficial for cutting thick roots (~0.38 in) • Creates holes quickly and consistently without compression • Best for shallow soil or sites with harsh conditions • Used primarily in loamy, sandy, or pumice soils	• Designed for rocky soils • Withstands significant wear and tear	• Removes forest litter and competitive vegetation • Lightweight and simple to use • Quick and effective for site preparation	• Ergonomically beneficial • Increases efficiency • Has depth and angle precision

Photos by Gabriel Altieri (hoedad, planting bars, dibble, and auger), Matthew Aghai (shovel), Paul Aston, Aston MTB, Ltd. (scalper), Hallman (1991) (hammer-action), and BCC Plant the Planet (Pottiputki).

composed of guest and migrant workers from Latin America. While the H-2B visa program is a key asset to providing labor to the forestry sector, the program is hampered by a number of drawbacks. In 2022, only 66,000 visas were obtainable through application, with 33,000 visa applications being accepted at either half of the fiscal year. During the past 17 years, the estimated count of H-2B-certified positions has been cut by more than half: 24,650 were accepted in 2004, whereas only 11,117 were accepted in 2020 (Bier 2021). The demand for H-2B visas is projected to rise in the near term as reforestation efforts across sectors and ownerships increase. In addition to concerns regarding H-2B visa shortages, some organizations have rigid hiring practices requiring them to hire locally, within their Tribe, or to outsource labor elsewhere. A diminishing supply of reliable labor may prove to be challenging for these groups as they look to increase planting operations in the future.

As important as it is to build upon labor pools, retention of the current workforce is equally important. Compared with the array of benefits and incentives historically provided to the CCC planters, tree planters today receive less total compensation (i.e., wages, benefits, and support infrastructure). Tree planting is often externalized to contractors who bid and compete for tree-planting contracts across industrial and agency ownerships. As a result, the incentive structure is designed around maximizing productivity at minimum cost. Thus, planters are predominantly paid on a per-tree, per-project, or per-acre basis and are often only provided with minimal equipment (e.g., shovel or hoedad and a planting bag), transportation to the site, and rudimentary lodging throughout the duration of their contract (figure 2). Incentives for crews from other labor pools, such as AmeriCorps crews, prison crews, and volunteer crews, are also lacking, resulting in consistently high turnover.

Planter retention is also highly affected by the physical strain of the work. Tree planters exert significant energy to meet production expectations (figure 3). In Canada, planters receive universal healthcare and occasionally have physical therapists on staff to ensure they mitigate the physical toll on their bodies. Tree planters can expend the caloric equivalent of two marathons per day (Granzow et al. 2019, Hodges and Kennedy 2011, Paarsch and Shearer 1997). In addition to cardiovascular stress, planters experience musculoskeletal disorders in the neck, shoulder, and lower back as a result of bent postures for prolonged periods of time, significant repetition of motions, and continuous forceful muscle exertion (Granzow et al. 2018, 2019). An average 8- to 14-hour workday includes responsibilities and activities outside of planting, such as training, transportation, and seedling loading and unloading (Hodges et al. 2005, Luke 2014). Additionally, the nature of the work limits breaks, which are often only at the beginning and end of the work period (Hodges et al. 2005).

Input from Practitioners Regarding Current Practices

Current outplanting practices can be improved by working directly with those who are directly involved with the process (e.g., foresters, foreman, planters,

Figure 2. (a) Current-day tree planters are often provided with (b) planting tools and planting bags, and occasionally gloves or other personal protective equipment. In some cases, however, planters are required to purchase their own equipment. (Photos by Gabriel Altieri 2022)

Figure 3. Tree planting is a laborious and strenuous task, requiring crew members to exert large amounts of energy. (Photo by Gabriel Altieri 2022)

land managers, etc.). An informal study tracked planting operations in real time using social research methods, scientific information, and anecdotal knowledge. We reached out to organizations in the forestry industry across the Western United States to conduct in-person and remote interviews, remote surveys, and to shadow the various elements of their outplanting operations. Interview and survey questions were based on the following topics:

- Project management and objectives
- Species and stock type(s)
- Pre-planting logistics
- General planting
- Planting crew communication
- Post-planting logistics
- Planting process
- Overall satisfaction
- Crew demography
- Hiring capacity

A literature review of current outplanting practices informed interview questions, which were tailored to specific audiences (land managers, foremen, planting crew members, or inspectors). We obtained complete datasets from eight of nine organizations via interview and site visits in Washington (n = 3), Oregon (n = 4),

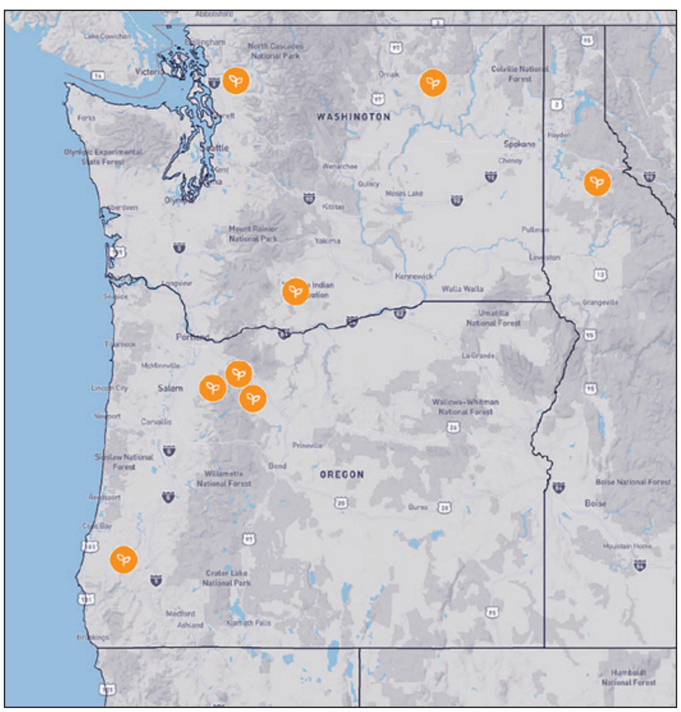

Figure 4. The study included site visits and surveys with organizations (orange markers) performing reforestation in Washington, Oregon, and Idaho, March through July 2022.

and Idaho (n = 1) (figure 4). Each organization was classified as either Federal (2), Private (n = 4), or Tribal (n = 2). After the remote and in-person interviews were completed, follow-up questions were sent to each organization as needed.

Data collection ran from March through July 2022. The approach was limited to capturing information surrounding spring outplanting efforts and was geographically constrained to the Pacific Northwest. While there is merit in collecting data throughout the autumn and winter outplanting seasons, most operations are contingent upon moisture availability, either as snow melt or rain, and the ability of nurseries to ensure seedling stock is prepared. Therefore, the most opportune time to collect data in the Pacific Northwest was during the spring planting season.

Before conducting interviews, we requested and received consent to take notes, collect data, and record both handwritten and electronic information. In-person site visits occurred whenever possible. These visits lasted approximately 1 full workday and involved facility tours, meetings with foresters tasked with managing seedling outplanting operations, shadowing and interviewing crew members involved with planting operations, meeting with inspectors, and capturing images. If the study team was unable to observe onsite operations, they conducted remote interviews or sent remote surveys to those organizations.

The objectives for the eight participating organizations fell into four broad categories: reforestation post-disturbance (e.g., wildfire; n = 2), reforestation post-timber harvest (n = 3), reforestation post-fire and post-timber harvest (n = 2), and restoration planting (e.g., riparian planting, natural restoration; n = 3). The organizations plant several species (table 2), with ponderosa pine and Douglas-fir being the most common and container-grown seedlings the most widely used stock type. Tools correspond with stock type, terrain, and soil conditions (figure 5), with shovels as the preferred choice when soil is easy to access and hoedads preferred for sites with heavy brush requiring scalping to clear competing vegetation. Data collected from the eight organizations are summarized in table 3.

Of the interviewees/respondents, 63 percent planted trees at 10- by 10-ft spacing (250 trees per acre; TPA) as per Rose and Haase (2006). Other spacing options were determined based on microsite availability,

Table 2. Several species are planted in the Pacific Northwest by participating organizations in the study to examine current outplanting practices.

Common name	Species name
Cluster rose	*Rosa pisocarpa* A. Gray
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Dune willow	*Salix hookeriana* Barratt ex Hook.
Geyer's willow	*Salix geyeriana* Andersson
Grand fir	*Abies grandis* (Douglas ex D. Don) Lindl.
Lodgepole pine	*Pinus contorta* Douglas ex Loudon
Noble fir	*Abies procera* Rehder
Ponderosa pine	*Pinus ponderosa* Lawson & C. Lawson
Port Orford cedar	*Chamaecyparis lawsoniana* (A. Murray bis) Parl.
Red alder	*Alnus rubra* Bong.
Redosier dogwood	*Cornus sericea* L. ssp. *sericea*
Scouler's willow	*Salix scouleriana* Barratt ex Hook.
Sitka willow	*Salix sitchensis* Sanson ex Bong.
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
Western larch	*Larix occidentalis Nutt.*
Western mountain ash	*Sorbus sitchensis* M. Roem.
Western redcedar	*Thuja plicata* Donn ex D. Don
Western white pine	*Pinus monticola* Douglas ex D. Don

stocking density, site history, and project objectives. Overall, planting spacing varied from 6 by 6 ft (1,210 TPA) to 15 by 15 ft (194 TPA) per organization. Elevations across planting sites ranged from 400 ft to 9,400 ft. As elevation increased at corresponding planting projects, TPA decreased. Planting elevations and species selection were also based on one another to match the ecosystem requirements of these elevations. Based on terrain, site preparation, and slope conditions, the quantity of trees planted per person per day varied between 278 and 2,000.

Differences in organizational infrastructure, internal bureaucracy, and standards for engagement with contracts influenced stakeholders' costs. For instance, when interviewing Tribal groups compared with private groups, Tribal groups utilized a wider variation in spacing, reforested more acreage, and planted ~4.5 times more seedlings. Tribal groups also paid a 16-percent premium at $0.25 per seedling compared with $0.21 per seedling paid by private groups for contracted planters wages. Although Federal organizations have historically paid higher planting rates ($0.35 per seedling), there seems to be a shift in relative planting costs based on labor availability. One Tribe has recently increased pay compared with prior planting years

Table 3. Current outplanting practices in the Pacific Northwest vary among the eight participating organizations (one per row in the table) in the study to examine current outplanting practices.

Project objectives	Species	Stock type(s)	Tool(s)	Spacing (ft)	Elevation range (ft)	Average trees per acre
Reforestation post-timber harvest	*Pseudotsuga menziesii, Thuja plicata, Chamaecyparis lawsoniana*	Styroblock®, Plug+	Planting shovel, planting bag	10 by 10, microsite	500–3,200	300
Reforestation post-timber harvest	*Pseudotsuga menziesii, Thuja plicata, Tsuga heterophylla*	Plug+	Planting shovel, planting bag	8 by 8, 9 by 9, 10 by 10, microsite	400–1,100	413
Reforestation post-disturbance, restoration planting	*Pseudotsuga menziesii, Rosa pisocarpa, Salix geyeriana, Salix hookeriana, Salix scouleriana, Salix sitchensis, Cornus sericea*	Bareroot	Planting shovel, planting bag	6 by 6, 7 by 7, 8 by 8, 9 by 9, 10 by 10, 11 by 11, 12 by 12, microsite	2,000–9,400	295
Reforestation post-disturbance	*Pinus ponderosa, Pinus monticola, Larix occidentalis*	Styroblock®	Hoedad, planting bag	14 by 14, microsite	2,200–3,200	218
Reforestation post-disturbance	*Pseudotsuga menziesii, Pinus monticola, Thuja plicata, Tsuga heterophylla, Abies procera, Alnus rubra*	Bareroot, Styroblock®, Plug+	Hoedad, planting bag	13 by 13, 14 by 14, microsite	2,200–3,800	259
Reforestation post-timber harvest	*Pseudotsuga menziesii, Abies grandis, Pinus ponderosa, Pinus contorta, Larix occidentalis*	Bareroot, Styroblock®, Plug+	Hoedad, planting bag	8 by 8, 9 by 9, 10 by 10, 11 by 11, 12 by 12, microsite	3,411–4,885	300
Reforestation (post-fire and post-timber harvest), restoration planting	*Pseudotsuga menziesii, Pinus ponderosa*	Bareroot, Styroblock®, Plug+	Planting shovel, hoedad, Pottiputki, planting bag	8 by 8, 10 by 10, 12 by 12, microsite	2,400–2,900	400
Reforestation (post-fire and post-timber harvest), restoration planting	*Pseudotsuga menziesii, Pinus ponderosa, Larix occidentalis*	Styroblock®, Plug+	Planting shovel, planting bag	12 by 12, 13 by 13, 14 by 14, 15 by 15, microsite	2,500–5,000	200

Figure 5. Planters use a variety of hand tools, which vary by site conditions, stock type, soil type, and personal preference. Participants primarily used (a) hoedads and (b and c) planting shovels during planting operations observed in the study. (Photos by Gabriel Altieri and Matthew Aghai, 2022)

to accommodate their growing need for reforestation, increasing relative reforestation costs to $1.25 per seedling, which includes all aspects of the reforestation pipeline (e.g., seed sourcing, seedling production, site preparation, planting, and monitoring).

The most common challenges reported by the eight organizations were planting quality and handling (table 4). These issues include poor planting techniques (e.g., J-rooting, L-rooting, wasting or stashing trees, etc.) and improper handling during transportation (e.g., mismanagement of planting boxes, improper temperature regulation, etc). The second most common challenge was associated with terrain and site conditions and included problems with site preparation (e.g., budget or timing constraints) and planting difficulties because of site conditions (e.g., heavy brush, unfavorable soil conditions, and steep slopes). Some of these issues can be exacerbated by transportation distances (figure 6).

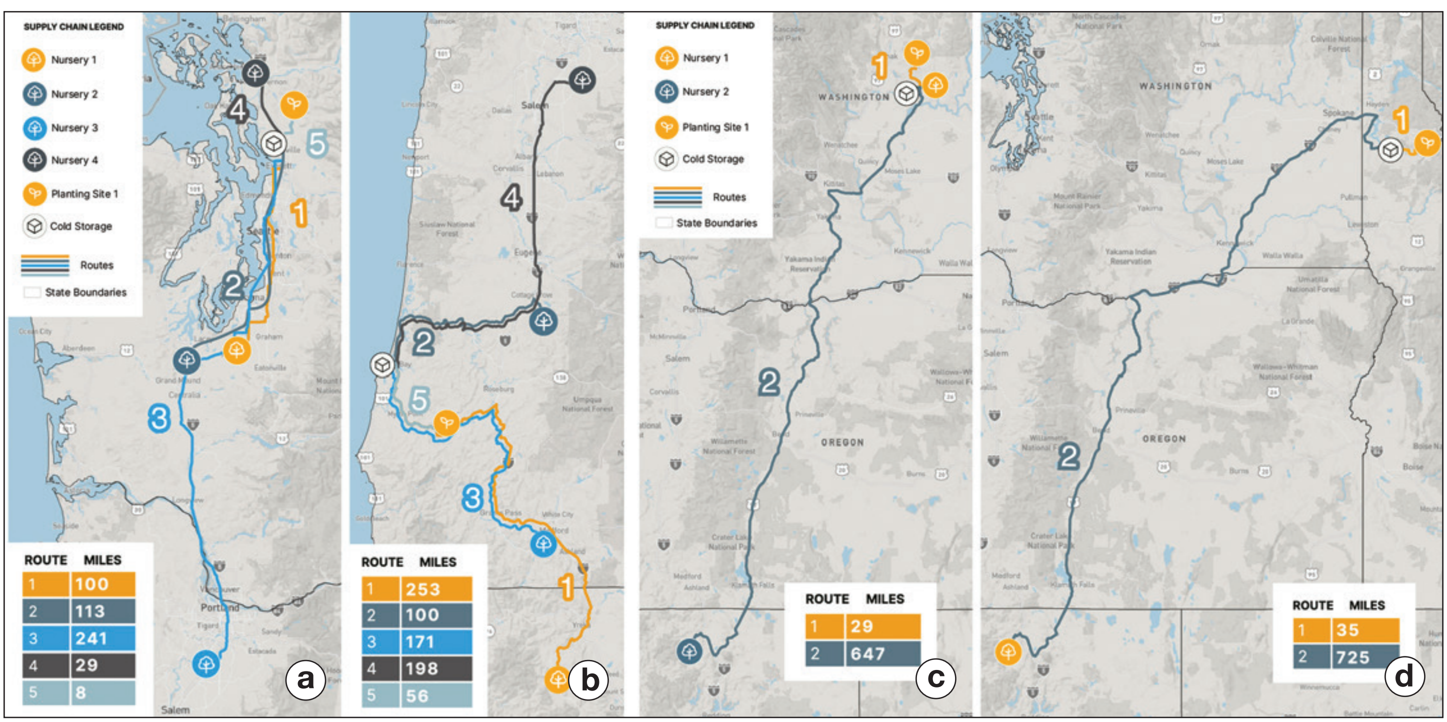

Figure 6. Seedling transportation distances between nursery source, cold storage, and planting site vary tremendously across organizations. Long distances require significant planning and labor. This image shows the transportation distance for (a) a private landowner, (b) a government agency, (c) a Tribal organization, and (d) a large real estate investment trust (REIT). (Source: Mast Reforestation 2022)

Table 4. Participating organizations identified various challenges to outplanting success.

Challenges	Percentage of organizations reporting challenge
Planting quality and transportation	78
Terrain and site preparation conditions	67
Nursery supply chain (e.g., seedling availability, quantity, species)	56
Seasonality and climate shifts	56
Labor shortages (e.g., crew members, inspectors)	56

Looking Forward: Addressing Planting Challenges

Improving outplanting capabilities involves addressing multiple pain points (table 4) in the reforestation supply chain. Site visits and interviews revealed how outplanting practices vary across organizations and indicate that future outplanting efforts will require significant investments. These efforts must be allocated towards education on quality planting practices and logistics, addressing difficult terrain and site preparation conditions, expanding nursery seedling capacity, adapting to climate and site environments, and expanding a trained labor force to ensure projects can be completed in the most scalable manner.

Planting Quality and Transportation

Planters and crewmembers must receive appropriate education and guidance to ensure that seedlings are properly handled when in storage, during transportation, and on the landscape to reduce risk of mortality. Based on discussions with planting supervisors, no formal education or training associated with tree planting is provided, mainly due to labor shortages. While formal training would increase the backend costs associated with tree planting, it could inherently increase seedling survival via proper planting and handling techniques and employee retention.

Because crew size varies, and the likelihood of only having one planting supervisor on site is high, supervisors are challenged to ensure that every planter is performing to the industry standard, which often involves the seedling “tug test” method. Inspectors perform this test with a three-finger gentle pulling technique at the top of the seedling (figure 7) to ensure proper seedling placement in the soil (i.e., correct depth, root orientation, and soil compaction) at the desired spacing. Respondents noted that sometimes inspectors were present to provide guidance to planters on their pace and planting quality, but this is the exception rather than the norm. Even with inspection, challenges with J-rooting, L-rooting, compacted roots, deep or shallow roots, and air pockets are recurring issues (Rose and Haase 2006) that require initial and ongoing education. Preliminary education could also involve shadowing an experienced planting team or supervisor during a training period. Additionally, a more direct working relationship among the forester, supervisor, and inspector would help ensure planting requirements are met. While creating and implementing a training regime for planters comes with additional expense, such an effort could greatly reduce expenses associated with planting mortality and replanting requirements, especially given that initial planting costs (e.g., seedlings, labor, and equipment) can range from $100 to $200 per acre, with the costs of replanting being even greater (Opalatch and Arney 2019).

Figure 7. Inspectors must ensure quality planting and compliance by (a) establishing plots and (b and c) excavating seedlings to measure stocking density and planting quality. The information from these plots is used to guide planting crews to make adjustments as per forester recommendations. Inspection plots also provide a sample area to project seedling survival. (Photos by Gabriel Altieri)

Planting quality is further influenced by contracts, planting tool(s), and nursery packaging. Achieving stocking densities by incentive structure (e.g., number of seedlings per day) requires significant physical exertion from planters, potentially resulting in substandard planting quality. This exertion may be ameliorated by the planting tool used. The Pottiputki, developed for improved ergonomics and productivity in the early 1970s, is a rare but prime example of coordination across reforestation objectives and nursery production standards. The design of the Pottiputki is intended to reduce physical and cardiovascular strain while maintaining planting productivity, comparable to other planting tools (Appelroth 1971). However, some problems with the Pottiputki make it difficult to use in a variety of ecosystems and terrains. These challenges include planting in hard or rocky soils, inability to plant a variety of stock types, and potentially increased risk of carpal tunnel syndrome and other injuries (Landis et al. 2010, Mullan and White 2002, Oliver and Rickards 2013). Clearly, more work in this realm is recommended, especially given that respondents reported problems with existing tools and equipment. For example, planting bags can fail due to excess weight, shovels are less effective in rockier soils, and hoedads, despite being the more suitable tool for conditions with significant brush, can produce planting holes considered inferior to those achieved using shovels. The quality of the planting, however, will be relative to each planter's planting technique, and the most suitable tool type is based on each planter’s preference (Adams and Patterson 2004). Moreover, planters noted that nursery seedling packaging could be problematic, especially when bags or bindings were too tight, making it difficult to grasp the bags and remove seedlings for planting.

In addition to training and proper planting, infrastructure investments are needed for sufficient and dependable seedling storage at the nursery, during transport, and onsite to maintain seedling quality and ensure the highest potential for survival and growth after outplanting.

Terrain and Site Preparation

Terrain, such as steep slopes, and site conditions, such as heavy brush and other competing vegetation, challenge land managers and planters. Before planting begins, land managers must prepare the site to facilitate the planting by clearing competing vegetation. Although site preparation is always of interest, it is not always achieved due to constricted budgets, low staffing, and short timelines. Multiple land managers in the survey cited an inability to adequately plan a planting operation. One Tribe explained that most of their budget for planting operations is derived from timber harvest revenue, which is prebudgeted to fund their site preparation and planting projects. While this Tribe has historically stayed ahead of the logistical curve, they explained that this revenue stream has been unable to meet the complete cost of site preparation and planting operations, despite their planning. Even when organizations have been able to meet required costs, adverse weather can hamper their ability to complete site preparation before planting. Nonetheless, advanced planning is critical to ensure all requirements are met before seedlings are planted.

In some cases, planters will seek out locations that are more advantageous for seedling growth, known as micrositing. Microsite planting involves positioning a seedling in a spot that provides it with the most favorable environmental conditions for survival (e.g., no vegetation, moist mineral soil, planting hole that is free of duff or debris, and partial shade from stumps, logs, debris, or dead brush) (Castro et al. 2021, Rose and Haase 2006). Based on interviews, reliance on micrositing is increasing as more foresters have experience to back the scientific validity of its efficacy. The micrositing technique may reduce planting efficiency and output, however, as it does not match the incentive scheme for the planters. Based on firsthand accounts with planters, foresters, and contractors in the field, a number of stakeholders explained that microsite-specific contracts significantly reduce the average number of seedlings planted per day per planter. Depending on the terrain and soil composition, a planter will plant an average of 1,200 to 2,000 trees per day. During microsite-specific contracts, however, the expected planting rate can be reduced to 800 to 1,000 trees per day. This shift not only reduces planting efficiency, but also reduces compensation for planters whose contracts are structured on a paid-per-seedling basis. Thus, increasing the adoption of outplanting techniques like micrositing will require a concomitant restructuring of compensation to planters, for instance to meet a per-contract milestone with certain quality assurance metrics.

Nursery Supply Chain

Nurseries have historically been equipped to meet seedling demand, but in recent years, both nurseries and nursery customers have had issues with the timing and seasonality requirements of seedling production. From a nursery customer perspective, one Tribal group informed us that their seedling order was cut in half due to the contracting nursery's inability to complete their requested seedling order in full. This was concerning for the Tribal group, as their grant funding for reforestation had to be used within a certain timeline, and it was unclear if a shift in their planting timeline could accommodate the delay in seedling availability. Similarly, obtaining seedlings has become more challenging across the industry for many stakeholders, with some offering to pay nurseries a premium for seedlings in order to meet their individual demand. One private forest management organization suggested that regardless of the size or resources available to a company, some stakeholders find it difficult to source and acquire proper seedling quantities for projects. These challenges may be attributed to factors such as seedlings being unavailable when planting operations are expected to occur regionally, or larger operations and real estate investment trusts (REITs) utilizing their capital to reserve nursery capacity at the expense of smaller scale customers.

The feedback provided by key stakeholders in the forestry industry demonstrates that many nurseries face infrastructural and logistical challenges in maintaining and expanding their seedling capacity. Expansion efforts are hindered by labor shortages, financial constraints, and market fluctuations as nursery seedling supply changes from year to year depending on project demand (Fargione et al. 2021). To address these issues, nursery education programs need to be implemented and enforced as a method to recruit newfound permanent and temporary nursery employees. Additionally, more research should be dedicated to improving various aspects of seedling production, including restructuring seed grading and processing, modifying growing timelines to accommodate shifting planting timelines, and adjusting fertilization regimes. These and other adjustments can increase efficiency in the seedling production process, therefore allowing nurseries to dedicate more resources towards infrastructure expansion and modernization.

Seasonality and Climate Shifts

Planting timelines are shifting in response to changes in climate. Thus, land managers and foresters must adjust planting windows to avoid adverse environmental effects on seedlings. To better define suitable planting windows, organizations have begun evaluating weather patterns to anticipate planting windows that may yield the highest seedling survival. One Federal organization suggested that ideal planting conditions occur when any sort of precipitation occurs on the landscape (e.g., minor snowfall, snowmelt, rain, etc.) immediately before or after planting. Tried-and-true recommendations will likely still apply, such as avoiding planting when the ground is frozen, during a moderate or greater snowfall event, and/or when seedlings have not been properly cold acclimated.

In the Pacific Northwest, many regions have had drastic increases in temperature perturbation, fluxes from snowfall to strong heat, and extended periods of heat and drought resulting in frequent wildfire events (Halofsky et al. 2020, Keeley and Pausas 2019). To accommodate these shifts, land managers are shifting their planting cycles to the end of the winter and earlier in the spring and incorporating fall plantings. A major challenge of this shift in planting timing begins at the nursery, as most regional forest nurseries sow seedlings to match the conventional growing season and take advantage of ambient growing conditions that reduce energy demands and complexity of operations. Conventional production strategies of regional nurseries have historically been driven by low seedling prices, which constrained nursery owners in their ability to invest in more formidable production systems, more complex logistical operations, and the staff needed to support them. In addition, modifications to nursery and preplanting transportation infrastructure will need to be supported by a flexible and readily available planting workforce with the ability to access remote planting sites in challenging weather conditions.

To ensure smooth transitions as planting windows shift, land managers and nursery managers must work directly and collaboratively to adjust seedling production schedules to enable seedling availability throughout the entire year. Success requires communication between land managers conducting the planting operations, the nurseries providing the seedlings, and the planting teams working on a seasonal status. This will require investments in nursery infrastructure that allow for environmental controls for production of seedlings that may be asynchronous to conventional growing seasons. Additionally, the need for seedlings available at short notice creates a need for improved research into seedling growth, rapid seedling hardening, and short-term cold storage in the context of planting prior to dormancy induction, analogous to "hot-planting" (Landis et al. 2010, Sheridan and Nackley 2022).

Labor Shortages

Surveys and interviews with Pacific Northwest reforestation professionals indicate that a macroscale challenge associated with outplanting is the lack of readily available labor across the forestry industry that is compensated with a heavy reliance on migrant labor pools. This challenge impacts organizations regardless of size and resources. There are simply not enough tree planters that can legally be employed to meet the growing industry demand.

Through the process of meeting with individuals pursuing careers in farming, forestry, or environmental science, including members of Indigenous American communities, migrant laborers, and guest workers from Latin America employed on a seasonal basis through the H-2B visa program, the study found that an increase in labor commensurate with anticipated reforestation demand is necessary. Tribes are less affected by the labor issue because they predominantly, although not exclusively, hire contractors within their community (figure 8). For most private and Federal stakeholders, the labor force is predominantly composed of H-2B visa guest workers, augmented by permanent residents residing in Oregon, Washington, Idaho, or California that have daily commutes of 1 to 4 hours.

Beyond the basic challenges of finding contractors and signing contracts, other issues, such as tardiness or failure to appear at planting assignments, have resulted in project failures. A Federal organization noted that they have experienced issues when trying to hire more planters because the H-2B portal system is poorly designed to address the challenging seasonality of outplanting. Laborers are needed at a certain time, and if that window passes, contractors must look elsewhere for work.

Labor shortage is not solely a Pacific Northwest issue. Currently, there are approximately 11,000 H-2B visa employment opportunities nationally within the forestry industry, most of which are for nursery and planting jobs (Bier 2021). To meet the proposed reforestation goal of planting 25 million acres by 2040 in the Western United States, the combined forestry sectors (private, Tribal, State, and Federal) would need to plant about 400 million seedlings annually (Fargione et al. 2021, Haase et al. 2022). Accomplishing this at a moderate pace (e.g., 1,200 seedlings per day per planter) would require 400 12-person crews (almost 5,000 planters) for approximately 70 total planting

Figure 8. Tribal groups predominantly contract for planting crews within the Tribe. Contractors are often individuals who were previous tree planters with the Tribe. (Photo by Gabriel Altieri, 2022)

days each year. Nationally, planting an estimated 3 billion trees annually (Fargione et al. 2021, Haase et al. 2022) at the same moderate pace would require 3,000 12-person crews (36,000 planters) during optimal planting windows, as seedlings cannot be planted year-round in most of the country. New approaches or dramatic modifications will be needed to accomplish these goals.

One option for meeting these ambitious goals is to reinstate a historic approach similar to that of the CCC where the human element of planting was adequately supported. This support would include wage increases, advocacy from biological experts and silvicultural practitioners, infrastructure support and improvements, educational opportunities, and diversification of the labor pool. Currently in Canada, the tree planter demography tends to revolve around college-age youth who are incentivized to take on seasonal employment opportunities through a mutual, cultural norm, provision of strong infrastructure through Federal facilities, and receipt of competitive wages. This program entices some planters to continue this work as a long-term career. Another approach is to increase and streamline the guest worker process. Collaboration with the agriculture industry and lobbying for an increase in the quantity and quality of H-2B visas is critical, as well as creating more concrete contracting standards to protect front-line workers who have historically been overlooked or exploited. Standards put in place elsewhere can be used as a guideline to meet these reforestation requirements.

Closing Remarks

Currently, existing and emerging technologies, such as growing usage of unmanned aerial vehicles (i.e., drones), helicopters, cable systems, and/or terrestrial solutions have potential to enhance artificial forest regeneration. These technologies can also help drive innovation, improve efficiency, and resolve logistical challenges associated with outplanting seedlings. To utilize these tools in the best possible way, advancements must be made towards revamping how seedlings are supplied, transported, and maintained while on site. Storage facilities and infrastructure must be increased to match nursery capacity. Communication between nurseries, foresters, and contracted crews will be a crucial component in automating these processes.

Indeed, communication must be streamlined to ensure that supply chain challenges, such as shifting planting windows, seedling shortages, and constricted labor pools are overcome. Without clear communication between organizations and contractors, the reforestation pipeline will be clogged. Reforestation requires a subset of complex planning via site maps, silvicultural design, species prescriptions, and materials transport. To ensure that projects are completed without blockages in the pipeline, data and communication between key stakeholders (e.g., land managers, foresters, nurseries, planters, etc.) will be crucial, given the remote challenge of many planting projects.

For the current state of the reforestation pipeline to meet the substantial goals set for the future, researchers must work closely with all parties involved in the reforestation pipeline. Looking backward, evaluating current practices, and looking forward enable assessment of the status of outplanting, pinpoint what has been successful and what has failed, and provide direction for future improvements. Reforestation goals can be met through investment and partnership development to ensure seedling survival at the front and back ends of the reforestation pipeline (Grossnickle and MacDonald 2021).

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The Finish Line: Post-Planting Activities Improve Reforestation Success

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Abstract

Post-planting activities are not able to remedy major missteps during the reforestation process. They are, however, an important tool to improve seedling vigor and survival in many situations and can have significant long-term impacts on the success and cost effectiveness of reforestation programs. With increasing reforestation challenges for land managers across the West due to invasive weed communities, drought, and other impacts driven by climate change, proactively planned post-planting activities will need to become a standard consideration for reforestation programs. Furthermore, improved reforestation success through the use of post-planting activities will help alleviate seed and nursery capacity constraints for many forest management organizations in the Western United States. This paper was presented at The Reforestation Pipeline in the Western United States–Joint Annual Meeting of the Western Forest and Conservation Nursery Association, the Intertribal Nursery Council, and the Intermountain Container Seedling Growers Association (Missoula, MT, September 27–29, 2022).

Introduction

Good site preparation and the planting of high-quality seedlings (Wagner 2005) combined with the Target Seedling Concept (Rose et al. 1990) are critical components of a successful reforestation program. The work is not complete, however, when the seedlings are planted. Post-planting activities also play a critical role in ensuring successful seedling establishment and pushing reforestation projects over the conceptual "finish line." Climate change and its associated forest stressors (e.g., drought and extreme temperatures), as well as increasing pressure from pests, diseases, and invasive weed communities, have placed more emphasis on site-specific, "precision-forestry" management approaches that include post-planting activities.

A recent survey of forest landowners (Fargione et al. 2021) indicated that only one-quarter to one-third of forest landowners in the Western United States invest in post-planting activities. The lack of post-planting activities is likely due to a variety of reasons, which are important to explore to better understand the underlying causes and to support the development and implementation of post-planting tools and activities to help meet current and future reforestation goals.

The current large influx of Federal and State reforestation funding provides an opportunity to not only scale up current reforestation pipeline practices but to review and improve those practices and objectives, including post-planting activities. With a constrained nursery capacity in the Pacific Northwest, and insufficient seed for certain species and ecoregions, ensuring that most of the planted seedlings survive and thrive will be an important contribution to minimizing pressure and bottlenecks on the reforestation pipeline.

Post-Planting Challenges

The main challenge to post-planting activities is that most of the variables driving seedling establishment success have already been set. Species, genetic seed source, and stock type have been selected, and the site has been prepared and planted with a certain number of seedlings. After planting, there are no remedies for poor seedling storage, handling, and planting practices, missed microsite planting opportunities, or having the inappropriate species or seed source onsite (figure 1). A high-quality seedling of the appropriate stock type and genetic source is still the foundation to reforestation success. Therefore,

Figure 1. Selecting the wrong species for a reforestation site has long-term negative consequences that can generally not be remedied by post-planting activities. (Photo by Florian Deisenhofer, 2017)

post-planting activities can only address a subset of reforestation challenges and cannot significantly change tree seedling performance if any of the important previous steps were missed or poorly executed.

Unprecedented droughts, megafires, a heat dome, and increasing invasive weeds, insects, and diseases have created significant new challenges for foresters over the last two decades (figure 2). Approaches that have worked in the past are increasingly less likely to result in acceptable outcomes in the future. The ecoregions where managing the water resource for newly established seedlings is paramount will expand significantly in the coming decades. Projects will have to take more site-specific considerations into account, including followup visits to investigate the causes of seedling stress or mortality. Accepting that "trees die" without any followup creates a critical vacuum in the process to continuously improve reforestation success. This viewpoint also impedes a productive relationship with seedling nurseries, which rely on customer feedback to help improve growing practices and target seedling traits.

Another challenge to post-planting activities is an output-oriented mindset to forest management. Organizations have historically focused on cost and process when setting reforestation budgets and measured success based on data, such as number of seedlings planted, acres reforested, acres treated, etc. As seedling, labor, and reforestation costs increase and the seedling capacity is constrained by seed and nursery capacity, it is even more critical to shift to an outcome-based reforestation mindset. Conventional output metrics are not aligned with long-term reforestation success. To improve the current approach, reforestation budgets and goals need to expand to target seedling performance metrics, such as survival, root development, percentage of acres appropriately stocked, time required for seedlings to be free

Figure 2. Nonmerchantable stands on low-productivity sites following wildfire, such as the Cornet-Windy Ridge fire south of Baker City, OR, create challenging decisions for land managers regarding reforestation. (Photo by Florian Deisenhofer, 2017)

to grow (figure 3), cost per surviving seedling, competing vegetation thresholds, and other measures. Such and approach would allow robust assessment of reforestation success and avoid the "plant-and-walk-away" approach.

A lack of useable performance data or capacity to analyze data to support the reforestation decision-making process contributes to the output mindset. As forestry organizations have grown leaner in expertise and resources, less internal capacity exists to summarize and analyze reforestation. Similarly, the capacity to incorporate external research through scientific literature, conferences, and research cooperative projects has been hampered. As data have moved from plot cards and spreadsheets to cloud-based databases and geographic information system dashboards, and remote sensing technologies become increasingly effective for monitoring young plantations, forestry has an incredible opportunity to apply advanced analytics and create meaningful feedback on reforestation performance measures. Those analytics are becoming even more important as the results of reforestation practices vary from year to year in response to increasingly frequent weather extremes. Longer term trend analyses and understanding seedling performance in extreme years will be indispensable for developing critical guidelines on best regeneration practices for a challenging future of reforestation.

Finally, vegetation management as the most important post-planting tool continues to be largely unpopular with the general public. Controversy around the use of herbicides, in particular glyphosate, has heightened public concerns around forest applications and which products are being applied. The forestry community has not been able to send an effective message that planting trees alone may not suffice to achieve adequate seedling survival rates to meet goals of forest restoration, carbon storage, wildlife habitat, water and air quality, and other benefits. Continued engagement with the public and education around forest regeneration activities are needed. The use of "control" plots within operational treatment areas could serve as powerful

Figure 3. To achieve predictable free-to-grow conditions requires selecting the right species, genetics, and stock type, and combining that with an effective vegetation management program including post-planting release. (Photo by Florian Deisenhofer, 2017)

visual examples to highlight the importance of continued post-planting forest management.

Types of Post-Planting Activities

Post-planting activities can be summarized into three broad categories: (1) minimizing physical damage to seedlings from animals, (2) minimizing seedling stress due to low water availability, and (3) monitoring seedling performance. Activities for each of these are summarized in the following sections.

Minimizing Physical Damage to Seedlings From Animals

Ungulate browse damage impacts seedling establishment and growth across many regions. Managing logging slash before planting along with microsite planting can significantly reduce post-planting ungulate browsing (figure 4). When slash is piled, it creates favorable planting microsites along the edges, and when it is left scattered, it impedes animal movement. Although tedious, moving slash after planting can protect susceptible seedlings. Slash plays only a small part, however, in the multipronged approach often needed to address browsing damage. Therefore, post-planting tools for browse prevention and reduction, such as repellents, bud caps, netting, tubes, and fencing, are useful depending on the site location, value of the planted seedlings (e.g., grafted orchard seedlings, or seedlings in research plots), and browsing severity (figure 5). An organization's objectives and budget priorities as well as the assumptions regarding the efficacy of the various treatments will determine what, if any, post-planting browse protection should be applied. One promising new alternative is a recently approved repellent

Figure 4. Microsite planting along an old down log, combined with manual slash placement (branch in front of the seedling) can minimize browse damage, which is particularly important for the first growing season. (Photo by Florian Deisenhofer, 2022)

Figure 5. Mesh tubes are commonly used to protect high-value or browse-susceptible seedlings from animal damage. (Photo by Florian Deisenhofer, 2022)

product on the U.S. market, Trico® Pro (Kwizda Agro GmbH, Vienna, Austria). This product has been shown to prevent browse damage for 6 months in early trials on western redcedar (*Thuja plicata* Donn ex D. Don) in western Washington (WADNR data, unpublished).

Cost and efficacy among the various treatment options vary substantially and need to be evaluated on a site-specific basis in conjunction with the management objectives. The best choice depends on factors such as species, length of protection desired, anticipated mortality, time delay for seedlings to be free to grow, stocking objectives, labor availability, assumed risk, local experience with browse severity, etc. As mentioned previously, the output-oriented mindset and the lack of data and analysis combined with a focus on short-term costs can get in the way of selecting the best option. A performance-based analysis to see which treatment option(s) result in seedlings that are free to grow in the shortest time and at the lowest long-term cost would be best. For western redcedar in particular, the cost of no post-planting protection can often be the most expensive pathway per free-to-grow seedling (figure 6).

A new study associated with the T3 Watershed Experiment (https://www.onrc.washington.edu/t3-watershed-experiment/), a collaborative research project between the University of Washington and the Washington Department of Natural Resources on the Olympic Peninsula in Washington, will compare various browse protection approaches for western redcedar and provide data to better support decision makers.

Minimizing Seedling Stress Due to Low Water Availability

With increasing frequency and duration of droughts, managing water availability to seedlings is the single most important step to ensure post-planting seedling survival. For high-value plantings such as seed orchards, irrigation is a common practice to ensure survival and establishment during the first few growing seasons. The Oregon Department of Forestry J.E.

Figure 6. Western redcedar seedlings planted in alternating rows with Douglas-fir on a site in the foothills of the southwestern Washington Cascades have still not reached free-to-grow condition after 12 growing seasons. (Photo by Florian Deisenhofer, 2022)

Schroeder Seed Orchard (St. Paul, OR) increased grafted seedling survival by more than 40 percent by proactively irrigating new orchards during the first two growing seasons (Kaczmarek 2022). With regard to traditional reforestation sites and climate change, regions that have been historically successful in ensuring adequate soil moisture with minimal vegetation management may need to increase active management of competing vegetation to minimize water stress. Additionally, retaining logging slash can contribute to soil water retention by minimizing the establishment of competing plant species (Harrington et al. 2013) and reducing heat and evaporation at the soil surface. Whole-tree harvesting methods, often combined with slash piling, have generally reduced slash loading across reforestation sites and thus reduced the potential for slash to significantly contribute to soil water availability for seedlings. For those sites, therefore, the most practical and financially feasible tool is to control competing vegetation, which minimizes soil water loss and increases light and nutrient availability.

Extensive research shows that controlling competing vegetation can tremendously increase forest productivity across North America (Wagner et al. 2006). Gonzalez-Benecke and Dinger (2018) concluded that preserving soil moisture until early August through vegetation management was critical for maximizing stand productivity for Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) in the Pacific Northwest. The greatest gains in forest productivity through water management are generally achieved in areas with challenging climatic conditions for survival, such as southwestern Oregon and on the east slopes of the Cascades in Oregon and Washington. In eastern Oregon, seedling survival increased significantly when vegetative competition was controlled through herbicides or weed mats; using tree shade cards (Terra Tech, Eugene, OR) also significantly improved survival, especially for seedlings that did not receive an herbicide treatment (Oester 2008).

The need for vegetation management and the magnitude of responses to treatments depends on climatic, topographic, and soil variables of the reforestation site, such as annual and growing season temperature and precipitation patterns, soil water-holding capacity, aspect, slope, and elevation. Wildfires often occur on low-productivity sites with poor water-holding capacity and low growing season precipitation, making them difficult places in which to quickly reestablish forests without vegetation control. Tree species and stock type, as well as the type and biomass of competing vegetation, are also influencing factors. Grasses and herbaceous vegetation have a significant effect on early seedling survival and growth (figure 7). The greatest threat to long-term survival and forest productivity is unwanted hardwoods and shrubs (Wagner 2005). Many competing woody plants can be effectively controlled with mechanical treatments (Balandier et al. 2006). Herbicides can be used to control all types of vegetation and are particularly efficient for controlling grasses and herbaceous vegetation.

Shallow-rooted tree species such as western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and western redcedar may need more vegetation management than deeper rooted, early seral species such as coast Douglas-fir or ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson). The Vegetation Management Research Cooperative at Oregon State University (VMRC) showed a correlation between initial aboveground

Figure 7. Ponderosa pine seedlings planted in the Carlton Fire Complex (2015) with post-planting vegetation control were two to three times more likely to survive than seedlings planted without vegetation control. (Photo by Florian Deisenhofer, 2022)

seedling size and vegetation management needs; seedlings with greater shoot volume needed more vegetation management, likely due to larger transpirational water loss (Wightman et al. 2019). When working with herbicides to control vegetation, particularly after seedlings have been planted, herbicide selection is critical to ensure no damage to seedling vigor aboveground or belowground. Seedling vigor post-treatment should be the primary response variable to determine treatment performance, not just vegetation cover. Damage to the roots by soil-active herbicides often goes unnoticed but can be particularly harmful, especially on tough or droughty reforestation sites (figure 8). Root damage can offset any benefits of improved soil water availability through vegetation management. Climate conditions play a critical role in herbicide breakdown. Thus, foresters in regions with cold and dry climates need to be particularly careful with timing and rates of soil-active herbicides.

Performance Monitoring

Significant advances have been made through the collection of seedling and plantation performance data and subsequent analysis. With today's advances in digital data collection and visual display in geographic information systems, processing and viewing large datasets across space and time—and making them easily available to anyone—are easier than ever. Obtaining reliable post-planting seedling performance data such as survival, growth, and damage, as well as competing vegetation data, can greatly increase the understanding of which factors are most responsible for driving reforestation success (or failure) and help prioritize any followup treatments, if needed. Common variables that can be analyzed for their correlation with seedling performance are nursery, stock type, species, planting season, planting contractor, planting quality, seedling storage length, seedling storage type, and herbicide rates. These annually collected datasets will not only highlight issues in a particular year but will also provide information on trends over time. Performance data build the foundation of a large-scale understanding of what works, what does not work, and where more research or different approaches are needed. Such data and analyses may show that practices that have been previously deemed unaffordable are actually critical to success.

Figure 8. Assessing the development of new root tips during the first season of planting is often the only way to identify damage from commonly used soil-active herbicides such as sulfometuron, metsulfuron, imazapyr, etc. Aboveground seedling appearance may not display any damage as seen in this 1-year-old ponderosa pine seedling excavated in late August of the first growing season. (Photo by Florian Deisenhofer, 2022)

The most important post-planting monitoring tool is a shovel. Ultimately, seedlings can only perform well when they grow roots. Thus, belowground examination of seedlings provides the most important assessment of field performance (figure 9). Establishment of common gardens is particularly helpful (without applying root-damaging herbicides) to provide a level playing field for all species, stock types, and nursery sources (figure 10). Digging trees during the spring and fall root-growth periods can be instrumental in under-

Figure 9. Belowground assessment of seedlings after outplanting is essential for assessing planting success. Ideally, seedlings will exhibit vigorous root growth such as (a) this container seedling planted in May and excavated in August 2022 near Colville, WA. Seedlings that appear healthy aboveground may have no new visible roots such as (b) this seedling when excavated in early October after one growing season near Nanaimo, BC. (Photos by Florian Deisenhofer, (a) 2022 and (b) 2019)

Figure 10. Common gardens are extremely useful test plots to identify seedling quality issues, assess root development, and test post-planting tools such as physical seedling protectors. (Photo by Brian Williams, Washington Department of Natural Resources, 2022)

standing tree seedling performance after planting. Seedlings can often appear healthy aboveground during the first growing season by living off stored carbohydrates from their life at the nursery. Only looking at roots can provide a true glimpse of seedlings' future performance potential and help trace problems back to their figurative "roots." Common gardens are also great communication tools between field foresters and nursery growers to facilitate feedback on operational performance of specific crops and to compare their success with others.

Benefits of Post-Planting Activities

There are several reasons to carry out post-planting activities. As described in the following sections, improved survival and growth are the primary objectives.

Survival

Post-planting activities to prevent expected regeneration failures are of foremost importance. Without survival, all investments into the seed, nursery, and outplanting components of the reforestation pipeline are lost. After planting, management goals are to overcome planting stress and establish the seedling on the planting site by root-soil contact as fast as possible (Grossnickle 2012). During the first few post-planting growing seasons, providing an environment safe from animal damage and with enough soil moisture in the seedling rooting zone is critical for survival.

Forest managers across the Pacific Northwest and Intermountain region have observed the rapid expansion of invasive weed species communities over the last two decades, such as woodland ragwort (*Senecio sylvaticus* L.), prickly lettuce (*Lactuca serriola* L.) and Canadian horseweed (*Conyza canadensis* L.) (figure 11). Those species have several traits in common, such as rapid growth and flowering, long germination periods during the spring and fall, large amounts of small, wind-dispersed seeds, and resis-

Figure 11. A thick cover of woodland ragwort often emerges in Pacific Northwest plantations during the first growing season following summer site preparation with herbicides and no post-planting release. (Photo by Florian Deisenhofer, 2022)

tance to commonly used soil-active forestry herbicides. Many landowners have documented an increase in forb cover following site preparation with herbicides during the first few growing seasons compared with control treatments. Since invasive forb species are adapted to aggressively exploit soil water resources in the same soil depth as newly planted seedlings (Cowden et al. 2022), they can be as, or more, competitive than untreated natural vegetation (Balandier et al. 2006). The competitive nature of invasive forb communities can be underestimated and lead to substantial seedling mortality, especially in drought years and on harsh sites.

In ecoregions with prolonged droughts, risk assessments to integrate seedling vigor, competing vegetation levels, site factors, and weather predictions are difficult, if not impossible (Schneider et al. 1998). Therefore, routine post-planting activities such as release from competing vegetation or shade card placement should be considered an "insurance policy" against above-average seedling mortality. In years with mild growing conditions, those treatments still provide a benefit to seedling vigor and growth, even when survival is largely unchanged, and they can mitigate undesirable seedling morphological characteristics such as high shoot-to-root ratios or poor root structures that may negatively impact seedling survival (Wightman et al. 2019). Regularly scheduled post-planting treatments generate more predictable outcomes of seedling survival with many long-term benefits. Closely monitoring hundreds or thousands of acres and rapidly responding to post-planting problems each year are challenging, whether due to constrained budgets, tight timelines, or limited personnel and labor resources. Proactive, preventative post-planting care decreases the overall establishment costs by minimizing replant and inter-plant acres to achieve desired stocking levels, decreasing the time needed to get stands free to grow, and reducing administrative workloads. On a broader scale, post-planting care saves valuable seed and nursery growing space for each organization, while freeing up capacity for the forest nursery sector.

Post-planting activities can also effectively reduce seedling mortality when unexpected challenges arise such as animal damage, frost damage, or lethal levels of competing vegetation. Those unplanned treatments are typically not as effective in maintaining seedling vigor as preventative methods because they commonly occur past the prime window of efficacy. Nonetheless, such treatments are still worth pursuing as they may still be able to salvage acceptable survival results and avoid the negative impacts described previously.

Growth

Post-planting activities can also enhance seedling growth, particularly stem diameter and volume growth, as stem diameter is more sensitive to competitive stress than height growth (Dinger 2018, Dinger and Rose 2009, Wagner 2005). Implementing post-planting activities can reduce the amount of time needed to meet management objectives, such as "green-up" requirements from State regulations, habitat thresholds, or carbon capture targets. This gain in seedling growth rates can be expressed as "age shift"—the number of years that trees with treatments are ahead compared with a control treatment. The VMRC analyzed data from 2 sites in Oregon after 20 growing seasons and showed that post-planting treatments generated age shifts between 0 and 10 years, depending on species and site (Gonzalez-Benecke 2021). Although some treatments were not operational, that research shows the incredible impact that post-planting treatments can have. In general, shade-tolerant species responded more to post-planting vegetation-management treatments than Douglas-fir, likely due to their being more shallow-rooted species and therefore more susceptible to drought stress.

Animal damage protection can also result in many years of age shift. A Washington Department of Natural Resources case study (unpublished) in southwest Washington showed a height difference of more than 700 percent after six growing seasons between western redcedar seedlings planted inside a fence compared with seedlings planted outside the fence (figure 12). Height growth of seedlings outside the fence was negligible for 6 years following the first growing season due to animal damage.

Studies looking at the timing of post-planting treatments generally show better survival and growth responses when treatments are applied in the first growing season (Gonzalez-Benecke 2021). This time is when seedlings are most susceptible to environmental stress as they are getting established on the planting site. Once seedling vigor is compromised, such as through foli-

Figure 12. Fifteen-year-old western redcedar seedlings planted inside a fence (background) have experienced many years of "age shift" compared to seedlings planted outside the fence (foreground with forester and western hemlock naturals) on a site near Longview, WA. (Photo by Florian Deisenhofer, 2021)

age loss by ungulate browsing or water stress through competition, it takes time for seedlings to recover and resume normal growth. Delayed treatments beyond the first growing season, however, can still have significant benefits, especially when applied during challenging years.

Conclusion

Post-planting activities play a critical role in pushing seedlings over the "finish line" to survive and perform in the long term. These activities cannot address certain mistakes that may have occurred during the nursery or outplanting phase of the reforestation pipeline. The correct species, genetics, stock type, and especially the quality of the seedling combined with correct storage and handling practices are still central to a successful outcome. Post-planting activities do, however, have the capacity to significantly reduce the strain on the reforestation pipeline by minimizing seedling mortality and therefore saving much-needed seed and nursery space along with optimizing precious reforestation staff time and resources. Post-planting activities can greatly accelerate stand development, creating significant age shifts by pushing seedlings to a size and vigor whereby they are much less vulnerable to animal damage or induced stress from water competition. Most importantly, post-planting monitoring is a superior method to acquire the necessary data to drive continuous improvement and innovation in operational reforestation and help landowners adapt to new challenges brought on by climate change.

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Strategic Seed Management to Meet Reforestation Needs

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Abstract

When land managers consider seed management for reforestation, they need to be deliberate so that efforts can be proactive to events on the ground. With increasing demand for reforestation, seed has become center stage. Strategic seed management is knowing when to bulk seed and when to keep seed lots separate as well as understanding where and how to use that seed. This approach allows land managers to confidently select available seed for reforestation projects and contributes to the production of high-quality nursery seedlings. Considering exact seed collection locations, managing the seed quality, and choosing the best stock type for the seed on hand can lead to efficiency and success with seed inventories. This paper was presented at The Reforestation Pipeline in the Western United States–Joint Annual Meeting of the Western Forest and Conservation Nursery Association, the Intertribal Nursery Council, and the Intermountain Container Seedling Growers Association (Missoula, MT, September 27–29, 2022).

Introduction

Reforestation happens across the landscape for many reasons and in many ways. In most instances, reforestation starts with seed at a nursery (Dumroese et al. 2005). Selecting the appropriate seed is important for producing long-lived, healthy forest stands that can withstand the effects of climate or pests (Randall and Berrang 2002). Seed-use plans can be developed to inform land managers and help them be successful with reforestation efforts. These plans are also used to build annual cone-collection and seedling requests. A seed-use plan that is adaptive and includes as much information as possible is crucial for strategic seed management and deployment of that seed.

Seed management can be thought of much like the Target Plant Concept (TPC). The TPC guides users through a series of key considerations for choosing the best plant material for a given site (Dumroese et al. 2016, Landis et al. 2010). This same concept can be used for seed management and use, particularly with regard to limiting factors. When land managers consider objectives and constraints for seed, they often include risk analysis of seed movement. This risk analysis informs decisions for seed movement from a source environment to a planting environment (Randall and Berrang 2002). If the seed is difficult to acquire, one may be less likely to move it farther from the collection site for fear of limited survival results. Where predation could occur before germination, land managers may be unwilling to use seeds with limited supply for direct-seeding applications. If the seed is easy to acquire, one may be more willing to take those risks. Defining the available seed, seed needed, deployment locations, and planting need allows one to build a dynamic and effective seed-use plan (table 1).

Seed Deployment

In seed planning and use, knowing the geographic source of the seed is important for understanding where deployment is appropriate. Often, the planting location is not the same as the collection location. To prevent maladaptation, seed should be used in a location climatically similar so that the future trees are adapted to the environment they are growing in and will have the greatest potential for success (Randall and Berrang 2002). Seed is identified from a collection area defined as a tree seed zone (figure 1), species-specific zone (figure 2), or breeding zone (figure 3). These zones are guides that have been developed to aid understanding

Table 1. The Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) seed-use plan created for the U.S. Department of Agriculture, Forest Service, Mt. Hood National Forest shows all possible tree seed zones and breeding zones for this area, as well as the spatial overlaps that occur. This plan allows the user to input seed inventory according to how it was identified at collection, edit the columns with planting acres and planting density, and calculate the possible collection need.

Identified collection zone	Spacial overlap with these zones	Corresponding elevation (ft)	Operational planting acres	Trees per acre	Seedlings required (thousands)	Seed needs[a] (lbs)	Inventory (lbs)	Other seed (lbs)
042	042	<1,000	0	200	0.0	0.00	0.00	0.00
042	042/06012	1,000–2,000	0	200	0.0	0.00	0.00	0.00
042	042/06013	2,000–3,000	0	200	0.0	0.00	0.00	0.00
042	042/06014	3,000–4,000	0	200	0.0	0.00	0.00	0.00
042	042/06015	>4,000	0	200	0.0	0.00	0.00	0.00
451	451	<1,000	0	200	0.0	0.00	1.46	0.00
451	451/06012	1,000–2,000	0	200	0.0	0.00	0.00	0.00
451	451/06013	2,000–3,000	265	76	20.1	1.72	1.71	0.00
451	451/06014/06024	3,000–4,000	0	200	0.0	0.00	0.00	0.00
451	451/06015/06025	>4,000	0	200	0.0	0.00	0.00	0.00
452	452	<1,000	0	200	0.0	0.00	0.00	0.00
452	452/06012	1,000–2,000	0	200	0.0	0.00	0.00	0.00
452	452/06013	2,000–3,000	0	200	0.0	0.00	0.00	0.00
452	452/06014/06024	3,000–4,000	0	200	0.0	0.00	0.00	0.00
452	452/06015/06025	>4,000	0	200	0.0	0.00	0.00	0.00
462	462/06014	3,000–4,000	0	200	0.0	0.00	0.00	0.00
462	462/06015	>4,000	0	200	0.0	0.00	0.00	0.00
463	463/06015	>4,000	0	200	0.0	0.00	0.00	0.00
661	661/06012/06022	1,000–2,000	0	200	0.0	0.00	0.00	0.00
661	661/06013/06023	2,000–3,000	0	200	0.0	0.00	0.00	0.00
661	661/06014/06024	3,000–4,000	0	200	0.0	0.00	0.00	0.00
661	661/06015/06025	>4,000	0	200	0.0	0.00	10.58	0.00
662	662/06015/06025	>4,000	0	200	0.0	0.00	0.00	0.0
662	662/06022	1,000–2,000	0	200	0.0	0.00	0.00	0.0
662	662/06023	2,000–3,000	0	200	0.0	0.00	8.17	0.0
662	662/06014/06024	3,000–4,000	0	200	0.0	0.00	0.00	0.0
662	662	>4,000	0	200	0.0	0.00	0.73	0.0
671	671/06023	2,000–3,000	0	200	0.0	0.00	0.00	0.0
671	671/06014/06024	3,000–4,000	0	200	0.0	0.00	0.00	0.0
671	671/06015	>4,000	0	200	0.0	0.00	0.00	0.0
06012	06012/042/451/452/661	1,000–2,000	9,896	132	1,306.3	111.36	21.37	0.0
06013	06013/042/451/452/661	2,000–3,000	10,129	76	769.8	65.63	95.36	0.0
06014	06014/042/451/452/462/661	3,000–4,000	10,667	45	480.0	40.92	118.82	0.0
06015	06015/042/451/452/462/463/661	>4,000	4,455	28	124.7	10.63	14.21	0.0
06022	06022/661/662	1,000–2,000	0	200	0.0	0.00	0.00	0.0
06023	06023/661/662	2,000–3,000	0	200	0.0	0.00	0.50	0.0
06024	06024/451/452/661/662/671	3,000–4,000	0	200	0.0	0.00	50.86	0.0
06025	06025/451/452/661	>4,000	0	200	0.0	0.00	11.12	0.0
Totals			**35,412**		**2,701.0**	**230.26**	**334.89**	**0.00**

[a] Estimated seedlings per pound of seed = 11,730.

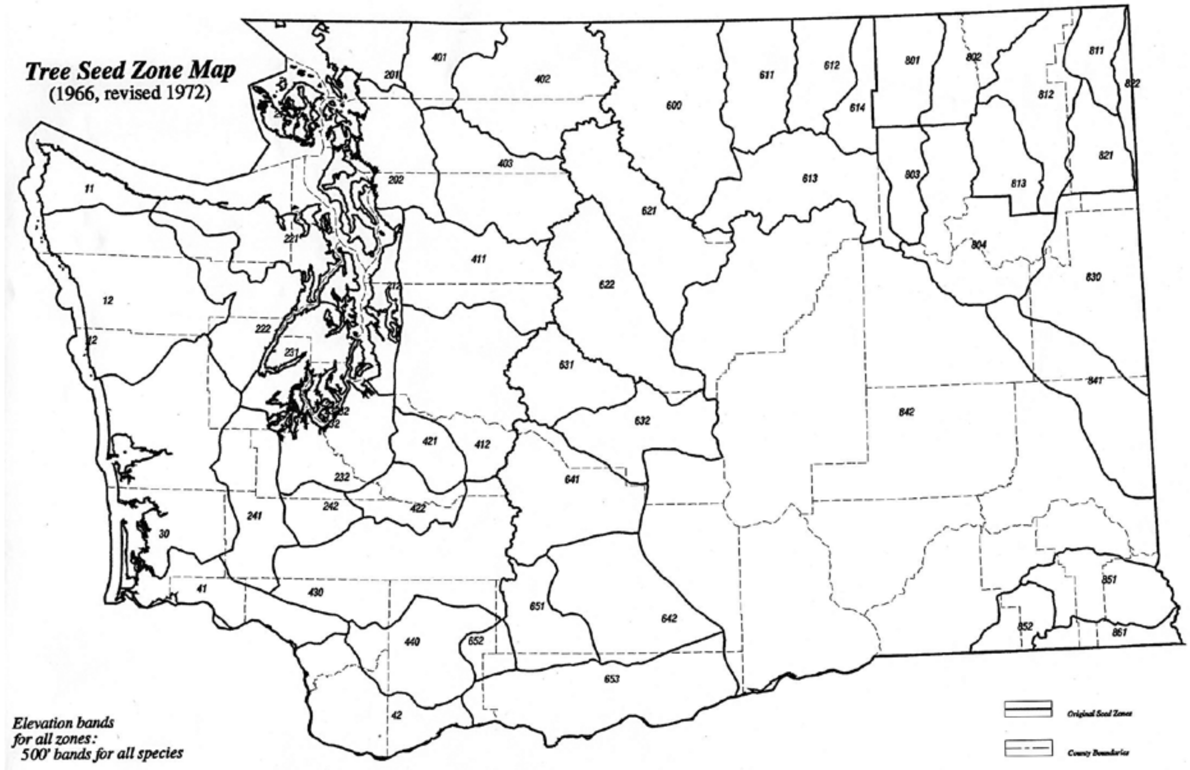

Figure 1. Generic tree seed-transfer zones were developed for Washington State and are used in conjunction with elevation bands to identify seed collections. (Source: Randall and Berrang 2002)

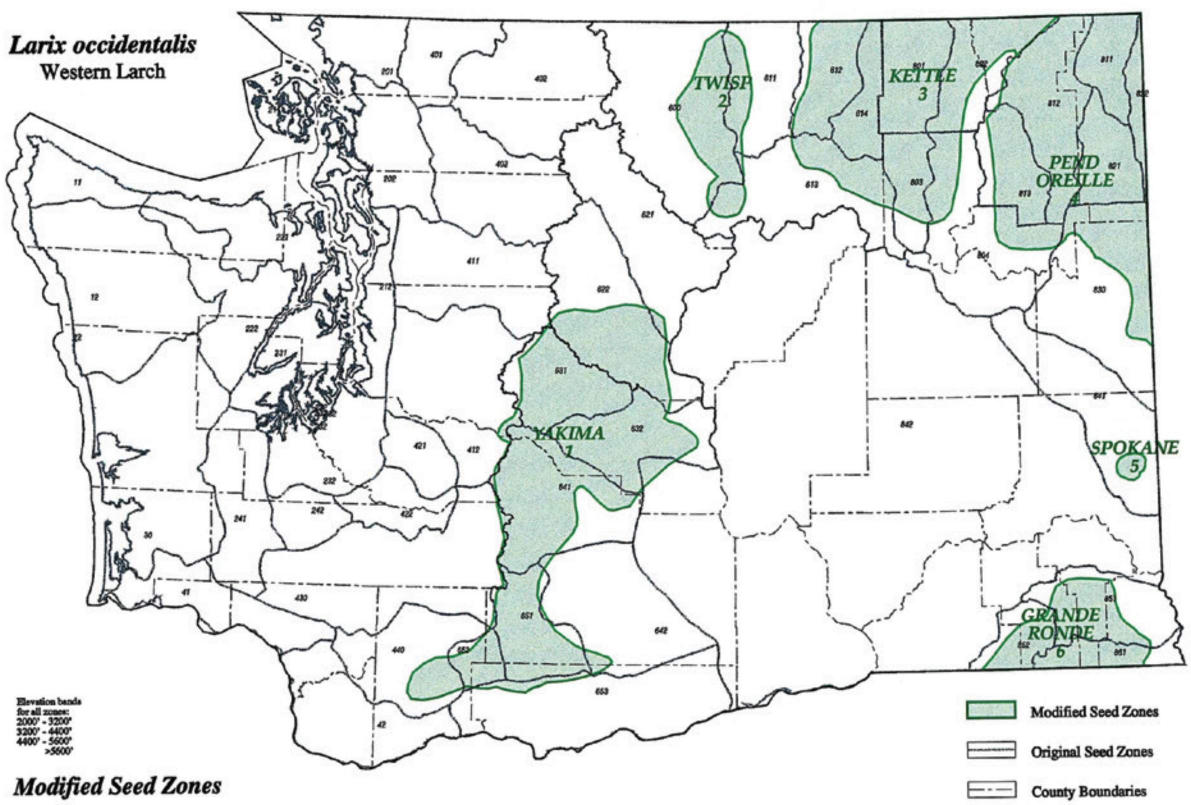

Figure 2. Species-specific zones, such as this one for western larch (*Larix occidentalis* Nutt.) within Washington State, have been developed for some locations. (Source: Randall and Berrang 2002)

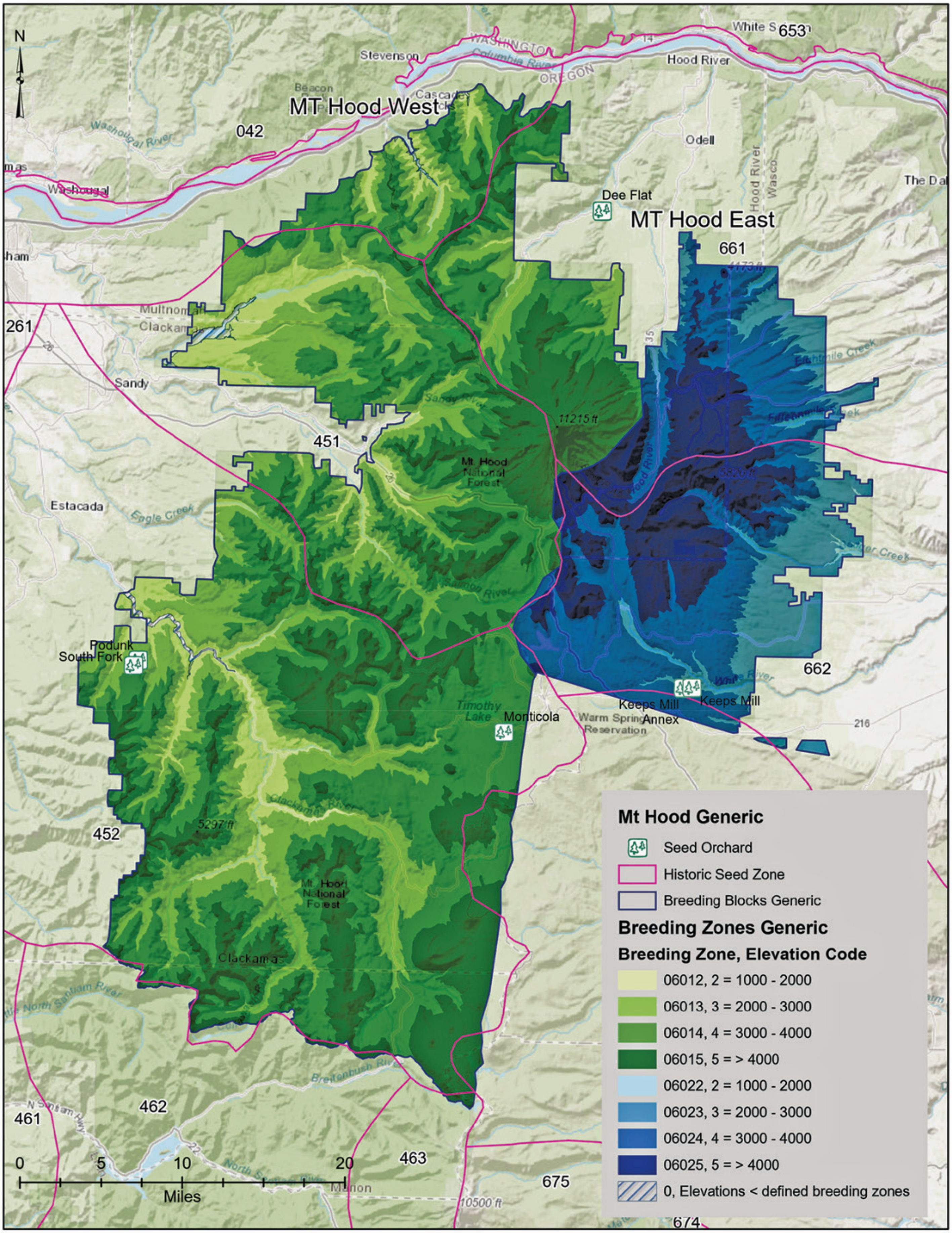

Figure 3. Overlaying a breeding zone map with tree seed zones allows users to better understand how to use older seed lots.

of seed sources and facilitate successful deployment (Buck et al. 1970, Randall and Berrang 2002). Common garden studies and assisted migration trials have resulted in increased understanding of seed-movement effects on plants (Schwinning et al. 2022, Silen and Mandel 1983). This work has also led to the development of tools, such as the Seedlot Selection Tool (St. Clair et al. 2022).

With the development of seed zones, collectors typically record only the zone and elevation information. Collecting exact geographic location, however, results in more flexibility for deployment. A seed zone is often a very large polygon across the landscape, thereby making it hard to pinpoint where seed came from if only the zone information is recorded. Depending on where the seed was collected from within the zone, it may or may not be able to cross into another zone. The edges of the zone could be quite far apart. For example, if seed is available from a zone that has a large geographic area, the north end and the south end may be very different. Seed can be moved within a zone with a high degree of confidence, but if the exact location is unknown, moving it outside of that zone could be risky. Exact geographic coordinates provide a better understanding of how far a given seed source can be deployed outside of that identified zone.

Strategic seed management examines where all possible zones overlap spatially. Breeding zones differ by species and forest and do not always match the seed zone polygons. Examining this overlap gives land managers the ability to better understand their seed on a map (figure 3) or in a tabular form (table 1). This examination identifies where the seed came from and where it could possibly be deployed, allowing for more dynamic management, flexibility of seed use, and the ability to use tools such as the Seedlot Selection Tool to guide deployment.

Deployment strategies and seed management are also affected by species characteristics such as genetic variation and adaptation capacity (Lu et al. 2014). As a result, modified zone maps for specific species have been developed (Randall and Berrang 2002). For example, a species like white spruce (*Picea glauca* [Moench] Voss) is tolerant of long-distance seed transfer and is predicted to cope well with climate change (Pike 2021). Thus, fewer seed lots are needed across the white spruce range. Red pine (*Pinus resinosa* Aiton), however, is projected to cope poorly with climate change (Peters et al. 2020) and has low genetic diversity (Pike 2022). Thus, more collection sites may be needed to capture red pine genetic diversity, but that would also allow for more options in seed deployment as the species can be moved large distances successfully (Pike 2022). When sharing seed across land ownership boundaries, labeling seed with the exact source location will be more important than ever to facilitate more deliberate seed movement.

Seed-Collection Challenges

Logistically, acquiring seed and planning for cone crops that are worth the collection effort can be hard. Cone crops do not always occur annually, so being strategic with seed management and deployment is important. Removing seed from the seed bank due to low quality should be done only when there is replacement seed available. Land managers can use low-quality seed for direct seeding rather than in a greenhouse where poor germination cannot be tolerated within limited space resources. Planning for seed collections on a seed-use plan is an important component of seed management to ensure adequate seed inventory as much as possible.

Seed Quality and Efficiency in the Nursery

Seed quality is another important aspect of seed management. Maintaining high-quality seed allows for nurseries to produce uniform, high-quality seedlings and helps to optimize efficiency of reforestation expenses (Barnett and McGilvray 2002). Seed-use efficiency has long been recognized as an important factor in nursery production (Landis and Karrfalt 1987). High seed efficiency minimizes oversowing or undersowing and potential seed waste (Barnett and McGilvray 2002). Nurseries continue to adapt and respond to increased demand for seedlings (Dumroese et al. 2005); in doing so, they are a resource to help land managers determine seed-collection needs and be efficient with available seed.

The economic impacts when using high-quality seed are often recognized, but creative ways to use the resource when quality has declined must also be considered. When seed germination is lower than desired, other strategies, such as supplemental direct seeding in addition to planting, can be considered (Godman and Mattson 1992).

Conclusion

Strategic seed management is difficult and complex. A good seed plan includes key information to inform land managers and seed collectors to optimize seed quality, efficiency, and quantity in a cost-effective manner. Strategic seed management is critical for nurseries to produce high-quality seedlings and for land managers to be successful in restoration efforts.

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Soil Moisture, Soil Temperature, and Seedling Growth in Response to Interspecific Competition and Woody Debris in Northern Idaho

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Abstract

A study evaluated the effects of varying levels of competing vegetation and coarse woody debris on microsite conditions around Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *glauca* [Beissn.] Franco) and western larch (*Larix occidentalis* Nutt.) seedlings at a high-productivity site and a low-productivity site in northern Idaho. Five vegetation-control treatments (0-, 25-, 50-, 75-, and 100-percent control) were maintained for 2 years. Soil moisture was positively influenced by the presence of coarse woody debris and negatively influenced by increasing levels of competition. Seedling stem diameter tended to be larger when there was less competing vegetation. The findings of this study bring together the common practices of vegetation management and slash retention, showing how both can create a more hospitable planting site by lowering soil temperatures and maintaining higher levels of soil moisture in the summer. This paper was presented at The Reforestation Pipeline in the Western United States–Joint Annual Meeting of the Western Forest and Conservation Nursery Association, the Intertribal Nursery Council, and the Intermountain Container Seedling Growers Association (Missoula, MT, September 27–29, 2022).

Introduction

Microsite factors at the individual seedling level influence seedling growth and survival after planting (Harrington et al. 2013). The microsite comprises the immediate area around a seedling, in which competing vegetation, woody debris, microtopographical variation, and other biotic or abiotic factors exert immediate influence on seedlings. These small landscape variations are considered either a benefit or detriment to tree regeneration. For example, in regions where soil moisture is a major limiting factor for seedlings, coarse woody debris left after harvest can cast shade on seedlings, thereby reducing heat load and soil evaporation, which, in turn, increases seedling growth and survival (Harrington et al. 2013, Sass et al. 2018). The presence and intensity of vegetation in the microsite can compete with the seedling for resources but could also modify the microsite environment around the seedling and ameliorate extreme conditions (Balandier et al. 2006).

Soil moisture is the main limiting resource in young plantations in the Northwestern United States. The region experiences an annual growing season drought from midsummer through early fall each year (Abatzoglou et al. 2014) that coincides with active seedling growth. Within the first few years after planting, seedlings are particularly sensitive to these seasonal fluctuations in available soil moisture since most of their roots are in the upper soil profile (Pinto et al. 2016). Because seedlings need water for transpiration and photosynthesis, dry conditions can result in smaller seedlings (Harrington et al. 2013). Lower soil moisture levels can also coincide with reduced nutrient availability (Nambiar and Sands 1993, Powers and Ferrell 1996). In addition to environmental factors such as air temperature and vapor pressure deficit, vegetative cover can drive these localized reductions in soil moisture due to transpiration.

Seedlings themselves can also contribute to moisture loss and their own demise. Seedling growth increases can result in subsequent tradeoffs in overall survival (Chen and Nelson 2020, Philipson et al. 2014, Simard et al. 2006). With increased growth comes an increase in resource demand, which can either result in realized growth gains or increases in mortality, depending on how and when site resources are limited.

As soil absorbs energy due to latent heat or direct solar radiation, moisture is lost to evaporation from the soil surface. The rate at which evaporative losses occur is typically slower compared with vegetative transpiration losses, as moisture levels are often higher on sites where vegetation has been controlled (Powers and Ferrell 1996). As the soil surface dries, the albedo of the surface increases, which reduces the impacts of direct solar radiation. A “drying front” forms, which disrupts the hydraulic connectivity between the soil surface and the moisture below, thereby slowing subsequent evaporative losses (Dingman 2015).

In addition to reducing soil moisture, high temperatures can pose a threat to seedlings. A study in northern Idaho on ponderosa pine *(Pinus ponderosa* Lawson & C. Lawson) seedlings showed that soil-surface temperatures above 131 °F (55 °C) resulted in irreversible damage to seedling tissues at the soil level (Kolb and Robberecht 1996). The same study found that the temperature of soil water used by seedlings was significantly colder than soil surface temperatures at midday. This finding suggests that higher amounts of subsurface soil moisture can ameliorate lethal effects of midday surface temperatures on seedlings. Increased access to soil moisture allows seedlings to transpire at a greater rate, leading to increased water content in stem tissues and thus acting as a buffer against tissue-damaging temperatures.

The effect of competing vegetation on microsite soil moisture and temperature and its impact on seedling growth is not well understood in the Inland Northwest. To address this gap in knowledge, this study examined the effects of incremental reductions in competition intensity on growing season soil moisture, soil temperature, and growth of western larch (*Larix occidentalis* Nutt.) and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *glauca* [Beissn.] Franco) seedlings at two sites that differed in productivity in northern Idaho.

Methods

Site Descriptions

The study included two sites in northern Idaho with differing site productivities (low and high) (figure 1). Site productivity classification was based on a modeled Douglas-fir site index for northern Idaho (Kimsey et al. 2008). The model includes a range of factors to estimate Douglas-fir productivity, including edaphic factors, such as parent material and ash mantle thickness; terrain factors, such as elevation, slope, and aspect; and environmental factors, such as mean annual precipitation. Site index (base age 50) was 104 ft (31.7 m) at the high-productivity site and 70 ft (21.3 m) at the low-productivity site.

The high-productivity site is located approximately 42 mi (67.6 km) east of Moscow, ID (46.671294 °N, -116.112895 °W). The site is situated at an elevation of 3,307 ft (1,008 m) above sea level, with an average slope of 16 degrees. The soils at this site are characterized by basalt parent material overlaid by a volcanic ash mantle. Average annual precipitation is 44 in (112 cm). The site has a northeast aspect.

The low-productivity site is located approximately 25 mi (40.2 km) east of Moscow, ID (46.700427 °N, -116.461105 °W). The elevation of this site is 3,376 ft (1,029 m) above sea level, with an average slope of 25 degrees. Soil parent material consists of gneiss and schist, with a mix of surficial volcanic ash and loess. Average annual precipitation is 37 in (94 cm). The site has a northwest aspect.

Both study sites are within operationally managed conifer stands. As such, each site was previously harvested, chemically site prepped, and then planted on a 10- by 10-ft spacing. The high-productivity site was chemically site prepped in July 2017 with a combination of glyphosate and imazapyr, and the low-productivity site was chemically site prepped in April 2018 with a mixture of glyphosate and atrazine. Both sites were planted in spring 2018. All seedlings were grown in 415C Styroblock® containers (91 cavities per block, 7.9-in^3 [130-ml] rooting volume; Beaver Plastics, Acheson, AB) at a private nursery in the Pacific Northwest. The seed lots for both species were sourced from genetically improved seed orchards and matched the elevation and seed zone of the sites.

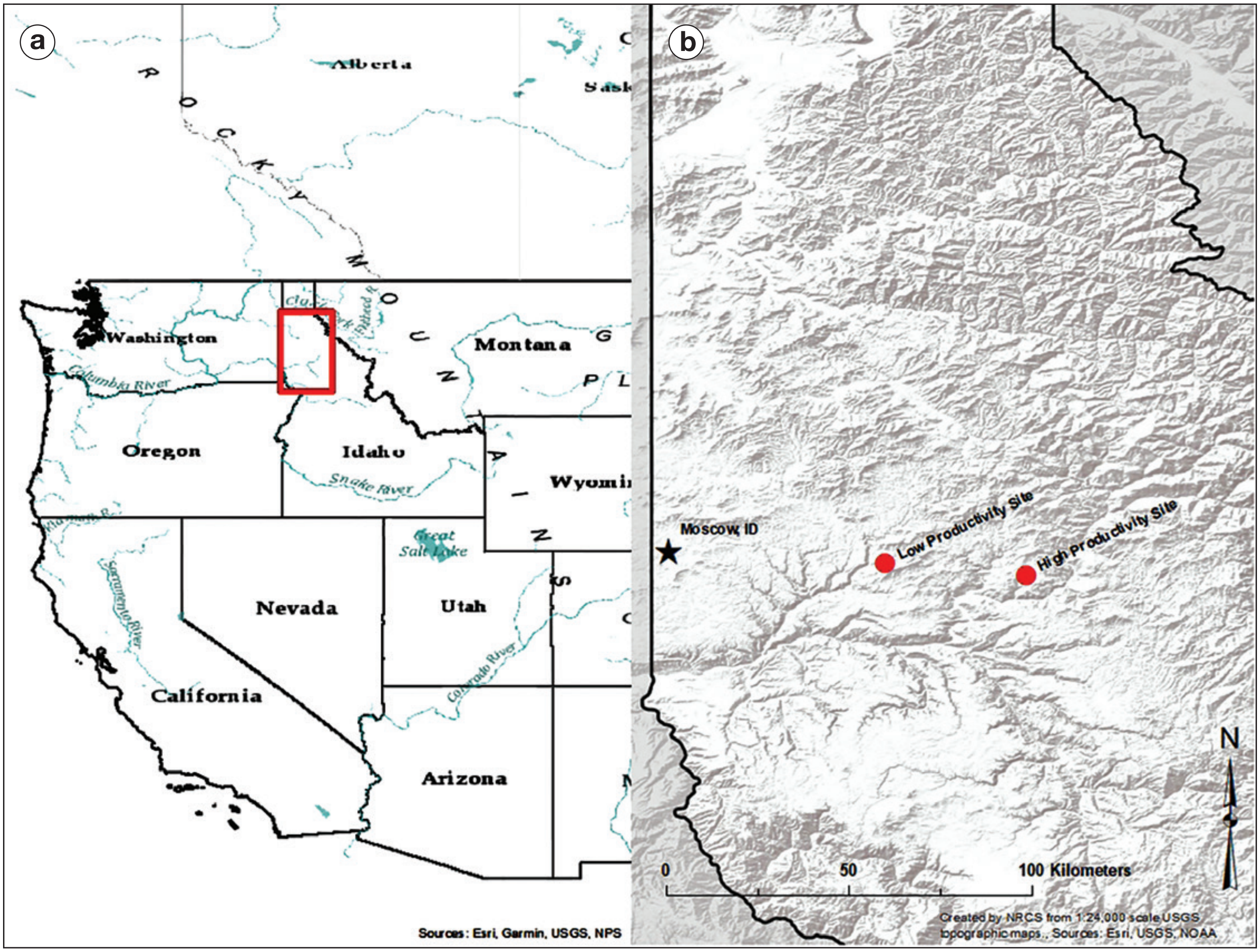

Figure 1. The study was conducted in northern Idaho. These maps show an outline of northern Idaho within the context of (a) the Western United States and (b) the detailed location of the two study sites.

Treatments

Thirty seedlings of each species (Douglas-fir and western larch) were randomly selected, tagged, and numbered at each site in May 2019. A 16-ft^2 (1.51 m^2) plot was delineated around each seedling and defined as the seedling microsite. Each plot was oriented with respect to the slope and then divided into four equal quadrats with the seedling located in the middle (figure 2).

The study contained five treatments, each randomly assigned to six seedlings per species. Treatments were 0-, 25-, 50-, 75-, and 100-percent vegetation control (figures 3 and 4) achieved via directed application of 7-percent glyphosate solution with 1-percent nonionic surfactant applied with a hand sprayer. Seedlings were protected from drift by a clear plastic bag placed over the seedling during application and removed after the herbicide dried (figure 5). After the initial herbicide application, treatments were maintained monthly as needed throughout the 2019 and 2020 growing seasons (May to September) using the same chemical prescription. When low densities of new weed germinants emerged between chemical applications, they were removed by hand instead of spraying with herbicide.

Measurements

Competing vegetation within each quadrat (percent cover by each plant species to the nearest 5 percent) before applying treatments (May 2019) and again in July 2019 and July 2020. Cover by species was summed in each quadrat and the mean total cover was calculated across the four quadrats. Due to this additive approach, total estimated cover within a

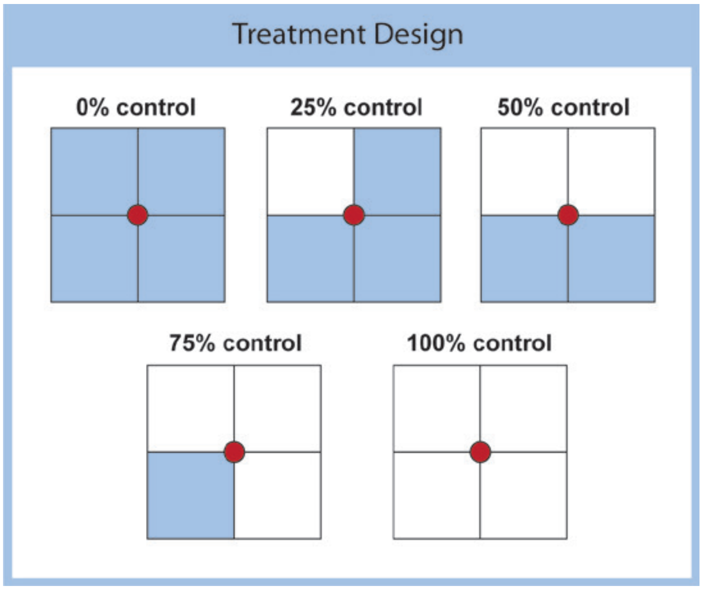

Figure 2. Treatments were designed to control competing vegetation in different quadrats around each seedling. The white squares represent quadrats that were frequently treated with glyphosate to maintain vegetation-free conditions, and blue squares represent untreated quadrats. The circle in the middle represents the planted seedling. Treatments were randomly assigned to each seedling.

Figure 4. In the 100-percent control treatment, all competing vegetation was controlled around the seedling in a 16-ft^2 square with the seedling in the center. This picture shows a 100-percent control treatment for a Douglas-fir seedling affixed with pink flagging at the high-productivity site 1 month after applying herbicide. The competing vegetation surrounding the control area reflects the intensity of competition around the seedling prior to treatment. (Photo by Andrew Nelson)

quadrat could exceed 100 percent for a given life form, as the foliage of multiple species could be layered vertically within the same area. In addition to competing vegetation, coarse woody debris cover (>0.4 in [10 mm] in diameter) was measured once during the study (July 2019).

Microsite environmental conditions were quantified by measuring soil moisture and temperature. A portable time-domain reflectometry soil moisture probe (HydroSense II, Campbell Scientific, Logan, UT) was used to measure soil moisture from May through October each year. The 7.9-in (20-cm) probes were inserted vertically into the mineral soil within each of the four quadrats around each seedling and within 6 in (15.2 cm) from the base of the seedling. Temperature sensors (iButton Thermochron, models DS1921G-F5 and DS1922L-F5, Maxim Integrated, San Jose, CA) were placed 0.8

Figure 3. All competing vegetation was completely controlled within a quadrat around a seedling based on the treatment. This picture shows an example of a 25-percent vegetation-control treatment around a western larch seedling at the high-productivity site. The seedling is located in the middle near the orange flag. The blue paint dots on the ground divide the microsite around the seedling into four quadrats. (Photo by Andrew Nelson)

Figure 5. Seedlings were covered with a plastic bag when glyphosate herbicide was applied to control surrounding competing vegetation, minimizing the chance of damage from herbicide contact. The bags were removed from the seedlings once the herbicide dried to avoid overheating. (Photo by Andrew Nelson)

in (2 cm) downhill from each seedling at a depth of 0.8 in (2 cm) into mineral soil in May of each year and set to record temperature at 1-hr intervals until October when they were removed (figure 6).

Root-collar diameter (RCD) of every seedling was measured at ground level in May 2019 when the study began and at the end of each growing season (October) for both years. Height was measured monthly from May (prior to initial treatment) through October of both growing seasons. During the May 2019 measurement, the height of the previous year's bud scar was measured to estimate height at time of planting. Survival was also monitored, although none of the seedlings died during the experiment.

Experimental Design and Data Analyses

The study installation was a completely randomized design with six replicate seedlings per species per treatment at each site. Each species at each site was analyzed independently for soil moisture, soil temperature, RCD, and seedling height using the R version 4.0.4 (R Core Team 2021). The total vegetation cover in July of each year was used as the competition covariate in all analyses. Main effects tested included year, total vegetation, and coarse woody debris. For soil moisture and temperature, month was also tested in the models. Soil moisture and temperature data were filtered to only include June, July, and August of each year to reduce noise and focus on the portion of the growing season in which moisture is most frequently limiting. For seedling RCD and height at the end of the growing season, initial RCD and height at the beginning of the study (May 2019) were included as covariates. The RCD and height models also tested soil moisture and August maximum soil temperature for significance, but both variables were consistently not correlated with RCD or height and thus dropped from the final models. Significance was determined at $\alpha = 0.10$.

Figure 6. iButton sensors (silver button near the seedling base) were buried immediately below the soil surface near each seedling to measure soil temperature throughout the two growing seasons. (Photo by Andrew Nelson)

Results

Soil Moisture and Temperature

Soil moisture decreased from May to August each year for both species at both sites (figure 7). Soil moisture was negatively correlated with vegetation cover except for the Douglas-fir plots at the high-productivity site (figure 8, table 1). Competing vegetation was negatively correlated with soil temperature only for the Douglas-fir plots at the high-productivity site ($p < 0.001$, table 2). Comparatively, coarse woody debris was negatively correlated with soil temperature in the western larch plots at both sites ($p < 0.001$). Soil temperature increased from May through August, with the greatest soil temperature of 87.5 °F (30.8 °C) at the high-productivity site in August 2020 and 92.5 °F (33.6 °C) at the low-productivity site in July 2019 (figure 9).

Seedling Morphology

Seedling RCD was negatively correlated with competing vegetation for Douglas-fir at the high-productivity site and western larch at both sites (table 3, figure 10). Comparatively, coarse woody debris was only correlated with western larch RCD at the low-productivity site ($p = 0.012$) but not any of the other species and site combinations. The only significant factor for total height besides year and initial height was competing vegetation for western larch at the high-productivity site ($p = 0.017$).

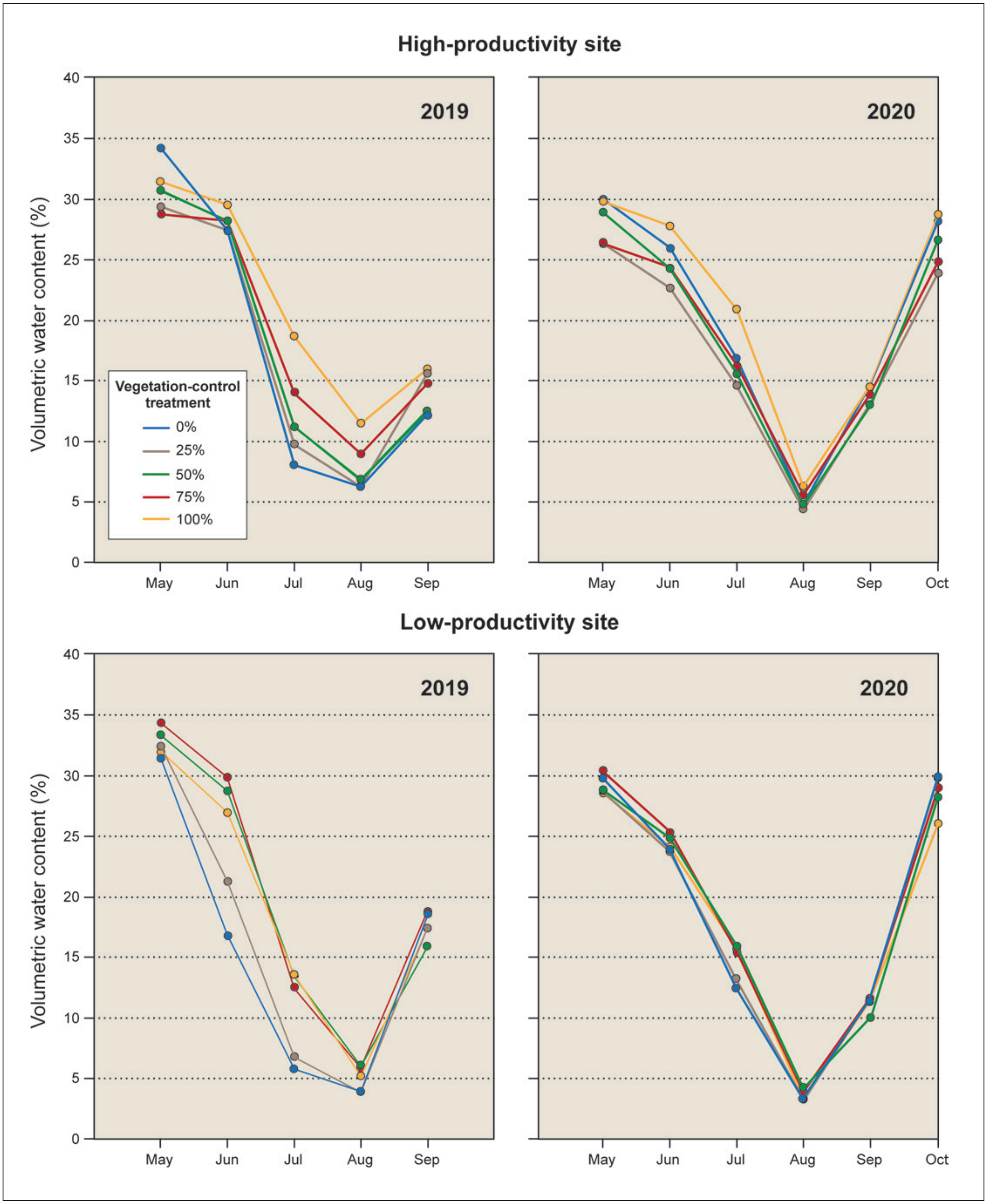

Figure 7. Volumetric soil water content decreased between May and August each growing season, reaching their lowest values in August after approximately 8 weeks of no precipitation. Soil moisture was relatively higher in the 100-percent control treatment at the high-productivity site during the summer drying period. Soil moisture then increased in September and October as fall precipitation occurred.

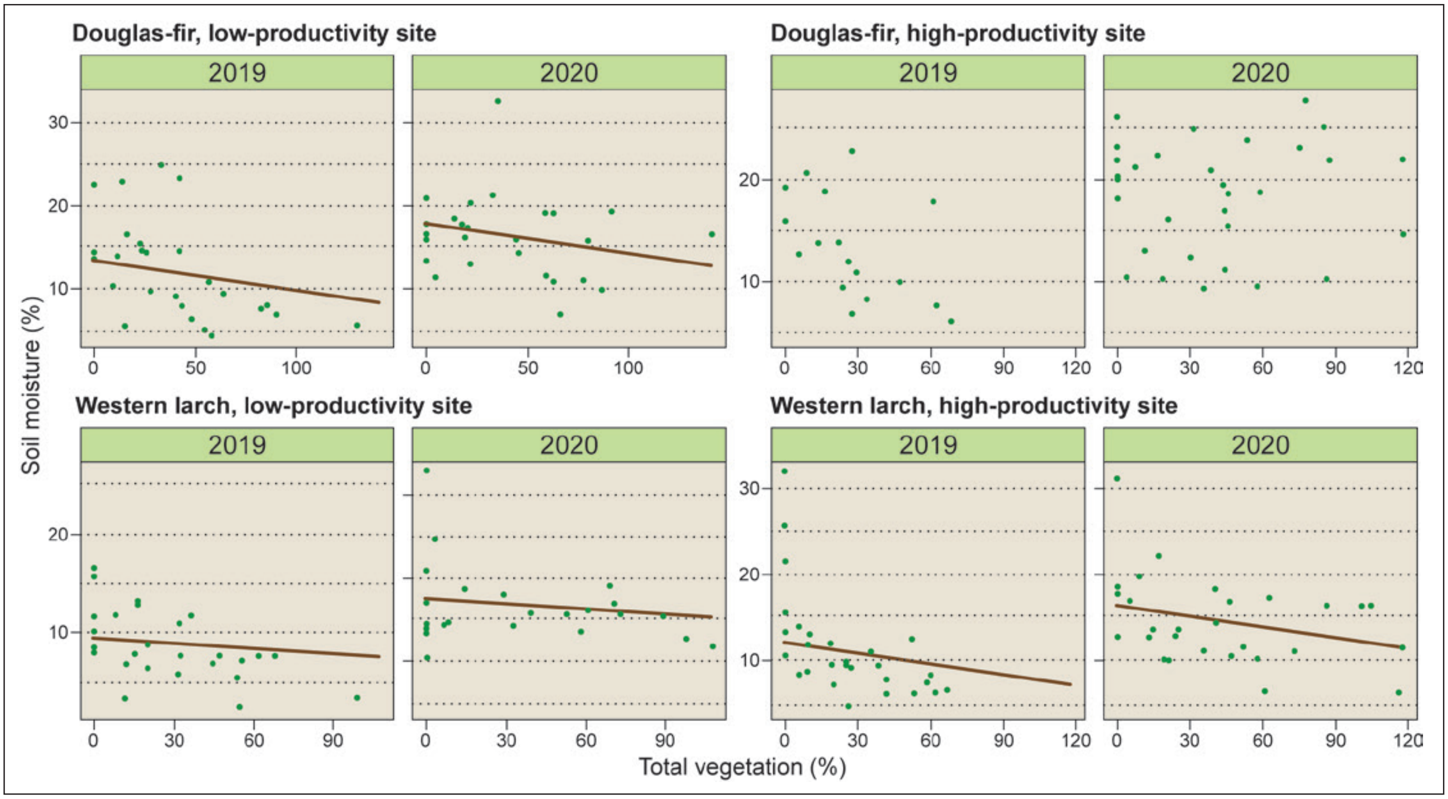

Figure 8. Soil-moisture in August was generally lower with increasing cover of competing vegetation around seedlings of Douglas-fir and western larch at the high- and low-productivity sites during the 2019 and 2020 summer growing seasons. The one exception was Douglas-fir at the high-productivity site, where competing vegetation and soil moisture were unrelated.

Table 1. P-values from the soil-moisture models for each species and site productivity combination. Significance was assessed at the $\alpha = 0.10$ level.

	Douglas-fir		Western larch	
	High productivity	Low productivity	High productivity	Low productivity
Year	0.317	0.118	0.425	0.836
Month	<0.001	<0.001	<0.001	<0.001
Total vegetation	0.931	<0.001	0.001	0.006
Coarse woody debris	0.013	0.761	0.856	0.001
Year x month	<0.001	0.008	<0.001	<0.001
Model adjusted r^2	0.7920	0.7902	0.7442	0.8349

Table 2. P-values and model r^2 values for soil temperature models. Significance was assessed at the $\alpha = 0.10$ level.

	Douglas-fir		Western larch	
	High productivity	Low productivity	High productivity	Low productivity
Year	0.005	<0.001	0.0155	<0.001
Month	<0.001	<0.001	<0.001	<0.001
Total vegetation	<0.001	0.665	0.835	0.617
Coarse woody debris	0.818	0.978	<0.001	<0.001
Year x month	0.003	0.912	0.001	0.039
Model adjusted r^2	0.5592	0.4155	0.4789	0.7125

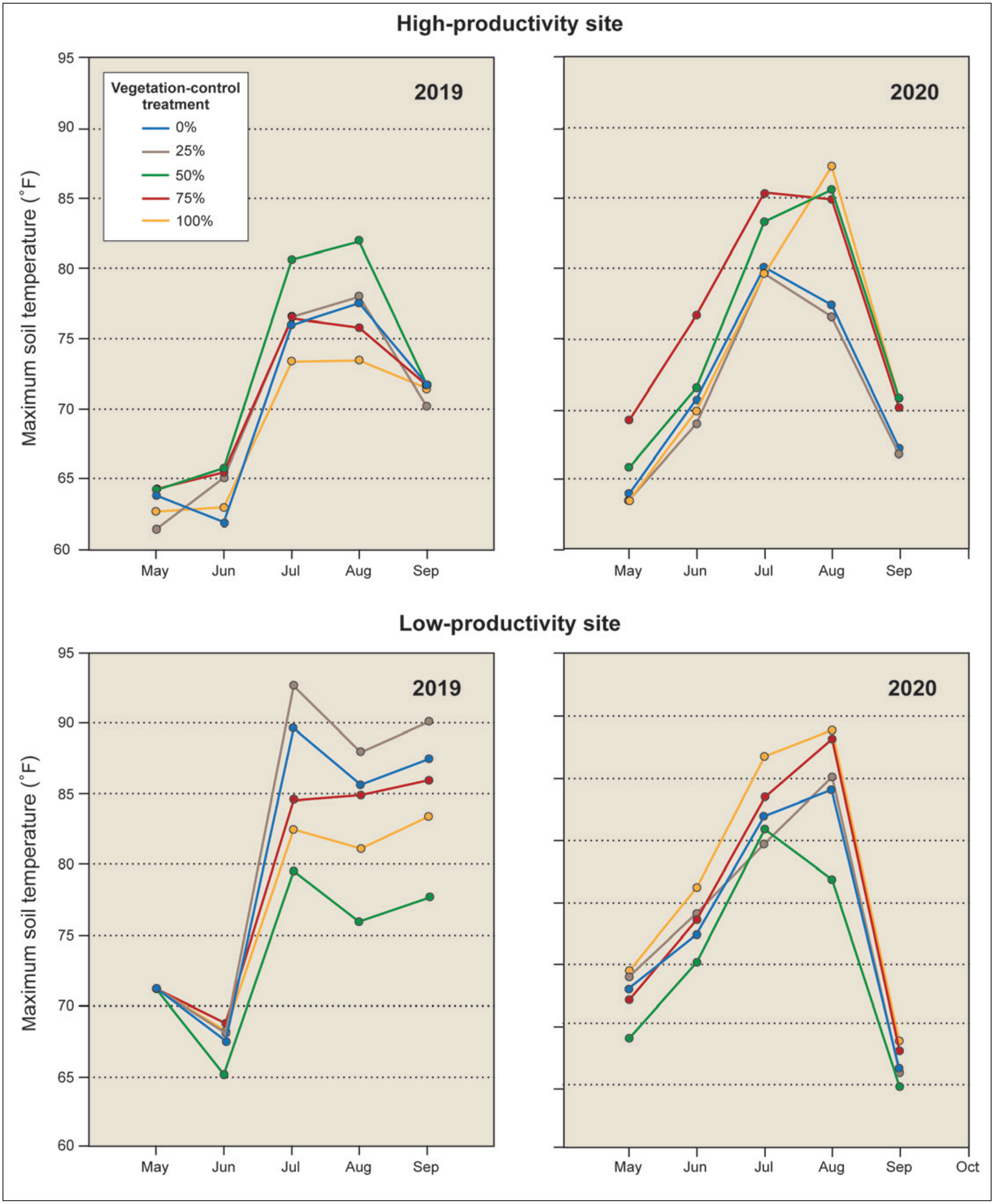

Figure 9. Maximum monthly soil temperature increased between May and August as air temperature increased and precipitation declined. Soil temperature peaked in August and then declined substantially except in 2019 at the low-productivity site where maximum soil temperature remained similar to soil temperature in August.

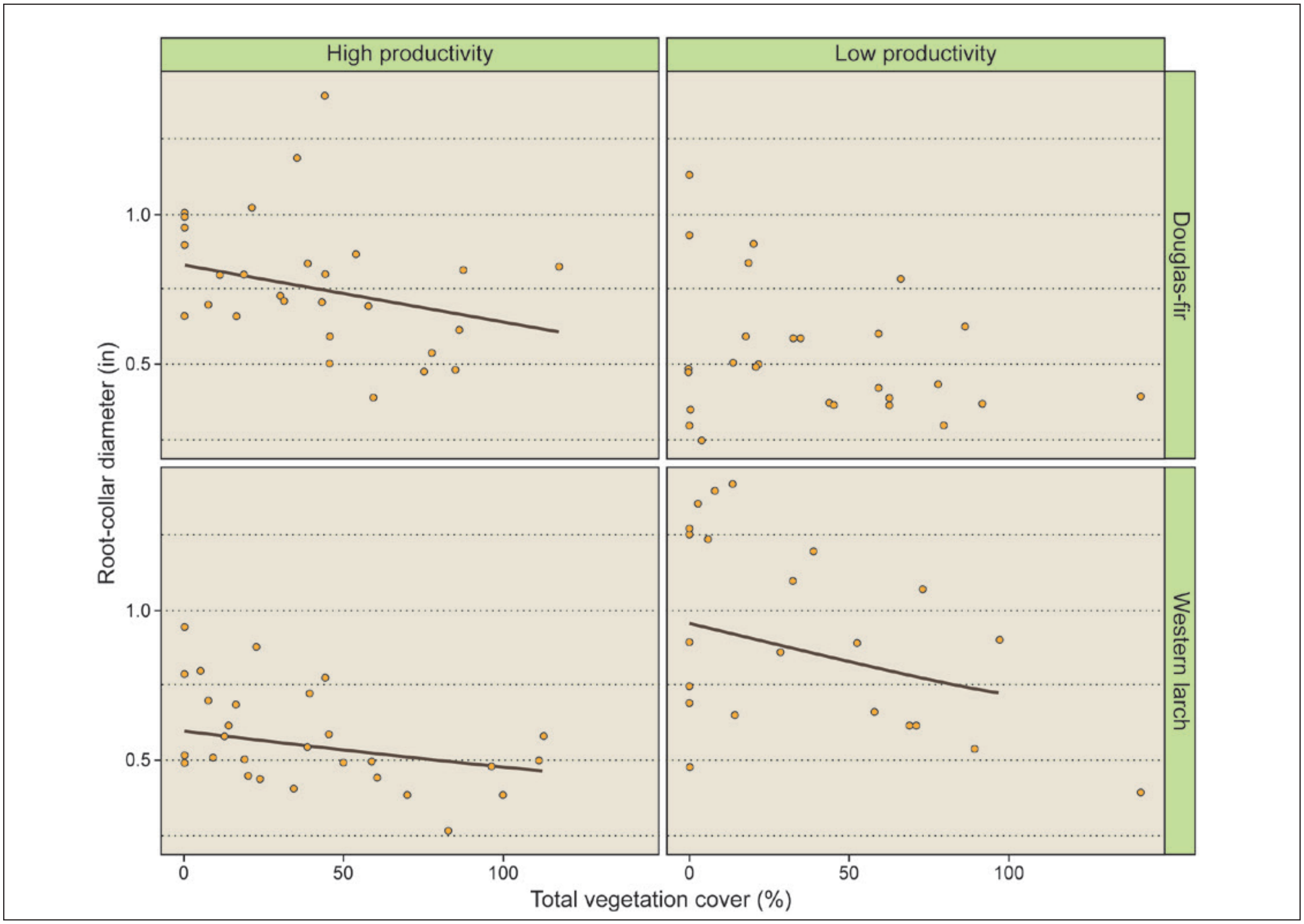

Figure 10. Seedling root-collar diameter (RCD) at the end of the second growing season (2020) was lower with increasing competing vegetation cover for Douglas-fir at the high-productivity site and western larch at both sites. A significant correlation between RCD and competing vegetation cover was not detected for Douglas-fir at the low-productivity site.

Table 3. P-values from analysis of second-year root-collar diameter and seedling height models for Douglas-fir and western larch seedlings assessed at the $\alpha = 0.10$ level.

	Douglas-fir		Western larch	
	High productivity	**Low productivity**	**High productivity**	**Low productivity**
Root-collar diameter				
Intercept	<0.001	<0.001	<0.001	<0.001
Year	<0.001	<0.001	<0.001	<0.001
Initial diameter	<0.001	<0.001	<0.001	0.004
Coarse woody debris	0.883	0.104	0.008	0.756
Total vegetation	0.022	0.111	0.019	0.059
Model adjusted r^2	0.7534	0.6868	0.6870	0.6314
Seedling height				
Intercept	<0.001	<0.001	<0.001	<0.001
Year	<0.001	<0.001	<0.001	0.011
Planting height	0.002	<0.001	0.018	0.047
Coarse woody debris	0.479	0.184	0.120	0.260
Total vegetation	0.173	0.606	0.017	0.322
Model adjusted r^2	0.5153	0.6899	0.4758	0.2604

Discussion

Soil moisture varied by growing season month, declining from May to August. This aligns with regional climatic patterns where precipitation is limited between early July and mid-September in northern Idaho (Abatzoglou et al. 2014). Total vegetation cover was correlated with soil moisture except around Douglas-fir seedlings at the high-productivity site. This negative correlation is well documented across the Pacific Northwest, including at a site with a similar climate in northeastern Oregon where soil moisture remained higher longer into the summer growing season when vegetation was controlled (Cole et al. 2018).

The positive correlation between soil moisture and coarse woody debris for Douglas-fir plots at the high-productivity site and western larch plots at the low-productivity site suggests that the debris may have reduced soil evaporation and limited suitable space for weeds to germinate and grow. Harrington et al. (2013) found similar results at two sites in western Washington and Oregon, where soil temperatures were negatively correlated and soil moisture was positively correlated with coarse woody debris; they attributed these results to less herbaceous cover. Similarly, Roberts et al. (2005) found that removal of coarse woody debris resulted in lower soil moisture, which likely occurred due to increased evaporation.

As summer progressed, soil temperature increased until reaching its annual maximum in July and August. Unlike soil moisture, total vegetation did not consistently influence soil temperature except on the high-productivity Douglas-fir site, where soil temperature was negatively correlated with competing vegetation. Increased amounts of vegetation may shade the soil surface, thus reducing surface temperature. Coarse woody debris was negatively correlated with soil temperature for western larch at both sites, which reinforces the possibility that shading from coarse woody debris may lower soil temperature. Devine and Harrington (2007) found that soil shading from mulch increased variation in soil temperatures, likely due to the scattering of material across the site.

The negative correlation between RCD and total vegetation at the high-productivity site was unexpected since resource competition tends to be greater on more xeric sites (Cole et al. 2018, Powers and Reynolds 1999). These studies and others have also found significant correlation between soil moisture and seedling size under different competition intensities, although soil moisture in the current study was not a significant factor. This difference from other studies could be attributed to the relatively mild moisture stress conditions during the 2019 and 2020 growing seasons. In addition, the volcanic ash mantle in the upper soil horizons has a high moisture-holding capacity (Kimsey et al. 2007).

Conclusion

Our results showing larger RCD with less competition supports prior research showing beneficial short- and long-term effects of vegetation control on tree growth (Cherico et al. 2020, Powers and Reynolds 1999, Wagner et al. 2006). Less often, these effects are paired with changes in soil moisture and temperature. Even though soil moisture was not a significant factor for seedling size, similar trends in correlations of lower soil moisture and RCD with greater competition suggests a link between moisture and size. Planting seedlings in favorable microsites may increase shade around a seedling, ameliorating some of the harsh effects of direct solar radiation during the summer on both the seedling and soil surrounding the seedling. The result is often increased survival and growth on harsh sites when proper microsite conditions are paired with competition control (Reely and Nelson 2021).

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Field Observations from Reforesting a *Typha*-Dominated Conifer Swamp in Southwest Michigan

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Abstract

Wetlands dominated by conifer trees are valued for wildlife, carbon sequestration, and commercial lumber production. Managers face unique challenges when reforesting these sites given the seasonally wet soils and variable hydrology. Black ash (*Fraxinus nigra* Marshall) is typically a component of these wetlands in the Lake States of the Eastern United States, but the species is disappearing due to the emerald ash borer (*Agrilus planipennis* Fairmaire, 1888). The loss of this species, competition from invasive plants such as cattail (*Typha* spp.), and climate change affect the delicate hydrology and subsequent tree regeneration in these sites. This article describes an observational study to assess success of planting native and nonnative tree species in a wetland area over 10 years. Northern white cedar (*Thuja occidentalis* L.) had the highest growth rate followed by eastern white pine (*Pinus strobus* L.). Growth of nonnative Atlantic white cedar (*Chamaecyparis thyoides* [L.] Britton, Sterns & Poggenb.) was higher than expected. Growth varied by species and tended to be influenced by duration of high water levels (especially during summer months). Canopy closure is expected to shade out competing vegetation an estimated 20 years after the time of planting.

Introduction

Wetlands dominated by woody evergreens, herein referred to as conifer swamps, are a relatively common forest type across the Great Lake States of the United States. Conifer swamps often host large densities of northern white cedar (*Thuja occidentalis* L.), tamarack (*Larix laricina* [Du Roi] K. Koch), white spruce (*Picea glauca* [Moench] Voss), and black spruce (*P. mariana* [Mill.] Britton, Sterns & Poggenb.). Wildlife use these tree species as a food source and winter cover (Curtis 1959, Doepker et al. 1990). These wetlands also provide habitat for rare plants (Epstein et al. 1999). Tree species, such as northern white cedar, also have strong cultural value to Native Americans (Meeker et al. 1993), such as the Anishinaabe people who have inhabited this region for thousands of years. Wetlands with healthy conifer trees have the advantage of year-round shade which can deter invasive plants from becoming established. For example, narrowleaf cattail (*Typha angustifolia* L.) or reed canarygrass (*Phalaris arundinacea* L.) are aggressive plants that can establish in gaps created by dead and dying overstory trees and reduce the overall biodiversity of the site (Hovik and Reinartz 2007). Conifer swamps are also threatened by human activities. For example, unintended consequences of poor restoration practices, such as tilling to increase soil aeration, can further degrade a site by altering water levels and lowering biodiversity (Cappiella et al. 2006). Many tree species that reside in these wetlands are predicted to decline, or experience range contraction, as a result of climate change (Prasad et al. 2007).

Black ash (*Fraxinus nigra* Marshall), a broad-leaved species that frequently inhabits conifer swamps across the Lake States, is being decimated by emerald ash borer (EAB, *Agrilus planipennis* Fairmaire, 1888), leading to rapid shifts in the hydrology (Slesak et al. 2014) and biodiversity of these forest types. Conifer species such as white spruce, northern white cedar, juniper (*Juniperus* spp.), pine (*Pinus* spp.), and tamarack are considered replacements to maintain tree cover on sites with declining black ash trees (Kesner and Nelson 2018, Palik et al. 2021). In the aftermath of extensive black ash dieback from EAB invasion, many wetlands are expected to revert from woodlands to grasslands dominated by *Typha* species and reed canarygrass (Bansal et al. 2019, Palik et al. 2012). These grasslands create new challenges for reforestation due to fluctuating water tables (Diamond et al. 2018), anaerobic soil conditions, and competition. Interestingly, leaf litter of conifer swamps releases less methane than wetlands dominated by *Typha* spp. (Emilson et al. 2018), so the post-EAB transition of these degraded sites to conifer-dominated swamps may play a unique role in carbon sequestration of this region.

Management tools and resources to revert *Typha*-dominated wetlands to conifer wetlands are scant. In addition, managers face numerous challenges such as identifying the optimal combination of tree species that can survive on these sites and procuring local seed sources. Changes in hydrology from shifting water tables can also interact with tree performance (Slesak et al. 2014) and are not well studied for any northern conifer species. Timing a reforestation effort to maximize survival is difficult, since most trees in the Northern United States are planted in the spring when water tables tend to be at a maximum from melting snow. Natural mounds are common in most unmanaged conifer swamps, and artificial mounds may improve success of planting upland tree species on lowland sites (Åkerstrom and Hånell 1997, Londo and Mroz 2001, Mehne and Mehne 2014, Reid 1985). The objectives of this report are to summarize observations from a reforestation effort on a wetland in southwestern Michigan, make suggestions for managers, and encourage future study to improve the success of reforestation on these valuable ecosystems.

Materials and Methods

Site Description

The site consists of a 4-ac (1.6-ha) conifer wetland on private property in Barry County, MI. The county is located at 42.5° N, 85.35° W in U.S. Department of Agriculture (USDA) plant hardiness zones 5b and 6a, corresponding to minimum temperatures of -15 to -10 °F (-26.1 to -23.2 °C) and -10 to -5 °F (-23.2 to -20.6 °C), respectively (USDA ARS 2012). The climate is continental with warm, humid summers, cold winters, and consistent precipitation year round (table 1). The site is 60 to 100 mi (100 to 167 km) south of the southern range edge of boreal forests in the northern Great Lakes region.

The vegetation on the study site is dominated by narrowleaf cattail, broadleaf cattail (*Typha latifolia* L.), and their hybrids, along with *Carex* spp., various forbs, reed canarygrass, and Phragmites spp. The grasses (*Typha, Phalaris*, and *Phragmites* spp.) are primary competitors to young trees and were 3- to 9-ft (1- to 3-m) tall across most of the site (figure 1). The wetland was classified as a northern hardwood swamp, but the Michigan Natural Features Inventory presettlement records indicate the likelihood of a prior conifer swamp with northern white cedar, black spruce, white spruce, and tamarack likely dominant before black ash became established (Comer et al. 1995). The wetland surrounding the site contains forested areas dominated by tamarack and black ash (figure 2).

Tree cover across the site was sparse and included tamarack, American elm (*Ulmus americana* L.), and eastern redcedar (*Juniperus virginiana* L.). Secondary species included quaking aspen (*Populus tremuloides* Michx.), black ash, eastern white pine (*Pinus strobus* L.), yellow birch (*Betula alleghaniensis* Britton), and red maple (*Acer rubrum* L.). Before EAB's arrival in 2012, black ash dominated portions of the site. The soil type for the entire wetland complex, including the study site, is Houghton muck, a poorly drained, deep organic soil. Holes dug in the wetland complex indicate that the organic matter is deeper than 6.5 ft (2 m) in some areas, and at least 3 ft (1 m) thick in most areas across the study site. Topsoil samples taken across the site had pH values of 5.6 to 5.9, and consisted predominantly of moderately decomposed to well-decomposed peat, originating from sedges or woody material.

Table 1. Normal monthly climate averages for the weather station in Hastings, MI, near the study area.

	January	February	March	April	May	June	July	August	September	October	November	December
High temperature °F (°C)	30 (-1)	34 (1)	44 (7)	57 (14)	69 (21)	78 (26)	82 (28)	80 (27)	73 (23)	60 (16)	47 (8)	1 (34)
Low temperature °F (°C)	15 (-9)	16 (-9)	24 (-4)	34 (1)	45 (7)	55 (13)	59 (15)	57 (14)	49 (9)	38 (8)	30 (-1)	21 (-6)
Rainfall in (cm)	2 (5)	2 (5)	2 (6)	3 (8)	10(4)	10(4)	4(9)	4(10)	4 (10)	3 (8)	3(8)	2 (6)
Snowfall in (cm)	19 (48)	13 (33)	7 (18)	2 (5)	0 (0)	0 (0)	0 (0)	0(0)	0 (0)	1 (3)	5(13)	16 (41)

Figure 1. In this overview of the planting site, taken in October 2020, the planted conifer trees are visible against the dense *Typha* species growing in the understory. (Photo by Alex Mehne)

Figure 2. Tamarack trees were prevalent along the periphery of the planting. (Photo by Alex Mehne)

Planting

In total, tree seedlings from more than 20 native and nonnative species were planted across multiple years (2011–2020) in December of each planting year (table 2). This article focuses on 11 species that had the highest survival, including five that are not native to the site, such as Atlantic white cedar (*Chamaecyparis thyoides* [L.] Britton, Sterns & Poggenb.), which grows in wetlands of the glaciated Northeastern and Southern United States (Laderman 1989). The number of seedlings planted per year and

Table 2. A variety of conifer species and seed sources were used at the study site in Michigan.

Species	Common name	Soil preference	Shade tolerance	Native biome	Seed source, rationale, and other details
Abies balsamea	Balsam fir	Upland	High	Eastern boreal forests	Native boreal species; may underperform because of expected range contraction with climate change; stock types and seed sources were variable.
Abies concolor	White fir	Upland	Medium	Western high-elevation forests	Upland fir species native to western States; favored by the horticulture industry; may be a replacement for balsam fir due to climate change; all stock types were 2-1.
Chamaecyparis thyoides	Atlantic white cedar	Lowland	Medium	Eastern temperate forests	New Jersey seed source; thrives in wetlands across the eastern seaboard where its habitat is threatened by development; not native to Michigan; grown from seed for 2 years in pots.
Juniperus virginiana	Eastern red cedar	Upland	Medium	Eastern temperate forests	Thrives in hot, continental climates; Michigan is its northern range edge; little is known about its performance in wetlands; all seedlings were transplanted from adjacent forests.
Picea abies	Norway spruce	Upland	Medium	Europe	Naturalized in Michigan; seed source unknown; stock types were variable.
Picea glauca	White spruce	Upland	Medium	Eastern boreal forests	Native boreal species; may underperform because of expected range contraction with climate change; stock types were variable.
Picea mariana	Black spruce	Lowland	Low	Eastern boreal forests	Native boreal species; may underperform because of expected range contraction with climate change; stock types were variable.
Picea sitchensis	Sitka spruce	Upland	Medium	Western high-elevation forests	Native to western States; grows on wetlands and uplands; best adapted to USDA zone 7 (Eckenwalder 2009) but may be cold hardy to mild winters (Sakai and Weiser 1973); western Washington seed source; all were 2-1 stock.
Pinus rigida	Pitch pine	Upland	Low	Eastern pine forests	Thrives in pine barrens in eastern States (e.g., NY and NJ); sometimes grows alongside Atlantic white cedar; not native to Michigan; all stock was 2-2.
Pinus strobus	Eastern white pine	Upland	Medium	Eastern temperate forests	Native to Michigan; occurs in adjacent stands, primarily uplands; stock types were variable.
Thuja occidentalis	Northern white cedar	Lowland	High	Eastern boreal forests	Native to Michigan and common in stands adjoining the study site; stock types were variable.

per species varied, and some were planted as replacements following mortality (table 3). Seedlings were planted at a spacing of approximately 7 by 7 ft (2 by 2 m). The seed sources for native species were a combination of local (adjacent counties) and nonlocal sources. All eastern redcedar seedlings, and a subset of balsam fir (*Abies balsamea* [L.] Mill.), white spruce, and eastern white pine seedlings, were transplanted from adjacent forests. Nursery-grown stock types were grown at a variety of nurseries. Roughly half of the seedlings were planted into mounds while the other half were planted directly into soil. Mounds were created using soil from the site (see Mehne and Mehne 2014). Dead planted trees were noted and replaced, either on the same planting spot or within 7 ft (2 m) of the original planting spot. Protective netting cones were placed around each planted tree to reduce incidence of browsing by white-tailed deer (*Odocoileus virginianus* [Zimmermann, 1780]) (figure 3). No herbicides were applied to the site.

Typha Removal

Two 0.1-ac (0.04-ha) plots were established for observing the effects of *Typha* removal on tree growth. *Typha* was removed mechanically (with brush cutters) on half of each plot and trees were measured from 2015 to 2017. The Wilcoxon rank sum test, a nonparametric t-test, was used to compare the removal and nonremoval plots.

Figure 3. Protective tubes were placed over the seedlings after planting to protect from herbivory. (Photo by Alex Mehne)

Tree Measurements

Tree height from the soil to the most distal living stem was measured with a telescoping height pole annually between November and January from 2012 to 2020 to the nearest centimeter. The difference in height growth from between the current (H_n) and previous year (H_{n-1}) is reported in figure 4. Relative growth was calculated as H_n / H_{n-1}; relative values greater than 1 indicate an increase in growth relative to the previous year. Surviving Sitka spruce (*Picea sitchensis* [Bong.] Carrière) trees (n = 39) were tracked for foliage loss (attributable to winter frost damage) each year.

Soil Temperature and Hydrological Assessments

Soil temperature was measured with a thermometer two to four times monthly during 2020 at each of three locations: south-facing shade, south-facing full sun, and north-facing full sun. Round dial thermometers affixed to metal stakes at different depths recorded belowground temperatures (figure 5). In addition, snow depth was measured weekly from November through January annually from 2012 to 2020.

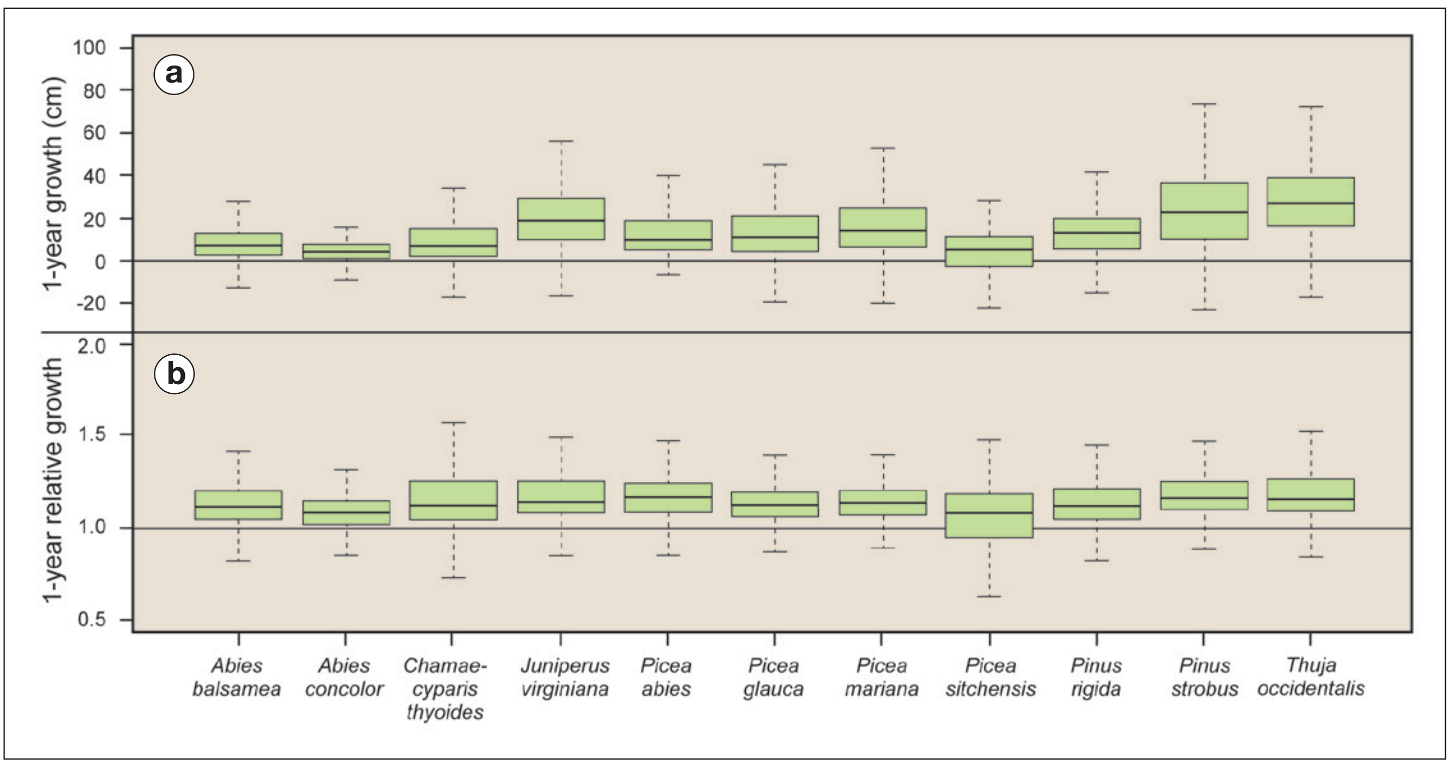

Figure 4. (a) Absolute height growth and (b) relative height growth from 2011 to 2020 for 11 tree species planted in a southwestern Michigan wetland. Midpoints represent median growth (annual increase in height). Outliers were omitted. The horizontal line represents no measurable growth. For a tree of height H (centimeters), growth of year n is defined as $H_n - H_{n-1}$ and relative growth is defined as H_n / H_{n-1}.

Figure 5. Water temperatures were monitored with round dial thermometers affixed to metal stakes at different depths to record belowground temperatures. (Photo by Alex Mehne)

Figure 6. Water levels were monitored with a measuring stick at 47 locations across the plantings. (Photo by Alex Mehne)

The study site included 47 pools set up for monitoring water table depth at random distances from each other. Water depth was measured weekly to the nearest 0.25 in (0.64 cm) at all pools (figure 6) during 2020. Pools that no longer had standing water were excavated and depth to the water table was recorded. Water table depth for each tree was estimated by georeferencing tree locations onto a raster calculated from an inverse-distance weight interpolation model.

The following hydrological variables were calculated to determine their association with tree growth by species: average and median water table heights, 5th and 95th quantiles for water table height, median water table height in July (driest month), and number of days water table height was above 0 (above the soil surface). Whether the tree was mounded or not mounded and whether the tree had been recently planted (within 3 years) was also noted. In addition, the number of days the water table height dropped below the soil surface to varying depths (<0, 0 to 5 in [0 to 12.7 cm], 5 to 10 in [12.7 to 25.4 cm], and >10 in [>25.4 cm]) was recorded. Kendall's rank correlation coefficient was used to observe the relationship between water table and 3-year height growth for six of the tree species. Mounding (with or without), initial tree height, and years since planting (>3 or <3 years) were included in the correlation analysis. All statistical analyses were run using R and QGIS software.

Results

Mortality occurred for most species during the first growing season after planting as reflected in the replacement rates (table 3). Survival data, however, were not closely tracked, so observations focused on the height of surviving individuals.

Tree Growth

Median height growth varied by species over time (figure 4). Eastern white pine and northern white cedar had the highest median annual growth. Trees with negative growth were shorter the second year due to dieback, infection, browsing, or frost heave. Minor frost damage occurred on select individuals

Table 3. The number of trees planted and the percentage replaced due to mortality varied by year and species.

Species	Common name	Number planted in 2011	Number planted in 2012	Percent replaced in 2012	Number planted in 2013	Percent replaced in 2013	Number planted in 2014	Percent replaced in 2014	Percent replaced in 2015	Number planted in 2011–2020
Abies balsamea	Balsam fir	92	89	13	6	6	0	6	4	187
Abies concolor	White fir	11	0	9	17	8	0	21	0	28
Chamaecyparis thyoides	Atlantic white cedar	0	7	0	82	19	43	5	11	132
Juniperus virginiana	Eastern red cedar	35	6	6	64	17	7	27	8	112
Picea abies	Norway spruce	1	1	0	0	30	28	6	9	30
Picea glauca	White spruce	20	131	20	95	30	4	3	3	250
Picea mariana	Black spruce	94	4	4	155	9	5	4	2	258
Picea sitchensis	Sitka spruce	0	103	14	0	18	0	7	16	103
Pinus rigida	Pitch pine	66	0	5	0	3	0	3	7	66
Pinus strobus	Eastern white pine	66	112	27	68	38	0	9	8	246
Thuja occidentalis	Northern white cedar	182	166	9	243	4	119	5	2	710
Sum /average %		567	619	10	730	1	206	9	6	2,122

of Atlantic white cedar in the fall for two of the years and Sitka spruce had extensive cold damage. For all surviving Sitka spruce, the number of trees with no signs of foliage loss from 2011 to 2020 was 24, 13, 3, 1, 3, 18, 32, 24, and 34 trees, respectively. Median height growth was negative in 2014 and 2015 but increased to 10 cm per year by 2020. The white pine weevil (*Pissodes strobi* W. D. Peck, 1817) affected eastern white pine, but overall height growth was not greatly diminished because lateral stems reclaimed apical dominance. In 2019, an unknown foliar disease on balsam fir resulted in partial to complete foliar loss in both healthy and unhealthy trees. Northern white cedar had the highest growth rates, with several individuals growing more than 18 in (46 cm) in a single year. Sitka spruce and white fir (*Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr.), the two taxa from the Western United States, had some of the lowest growth rates in 2020. Across species and years, stock types taller than 28 in (70 cm) but shorter than 63 in (160 cm) had the highest annual height growth (figure 7).

Effects of *Typha* spp. Removal

Survival of planted tree seedlings was initially poor in the two *Typha*-removal plots but improved over time (data not shown). Height growth tended to be greater in plots where *Typha* had not been removed. These differences in height growth were significant in both east and west blocks ($p = 0.001$ and 0.092, respectively).

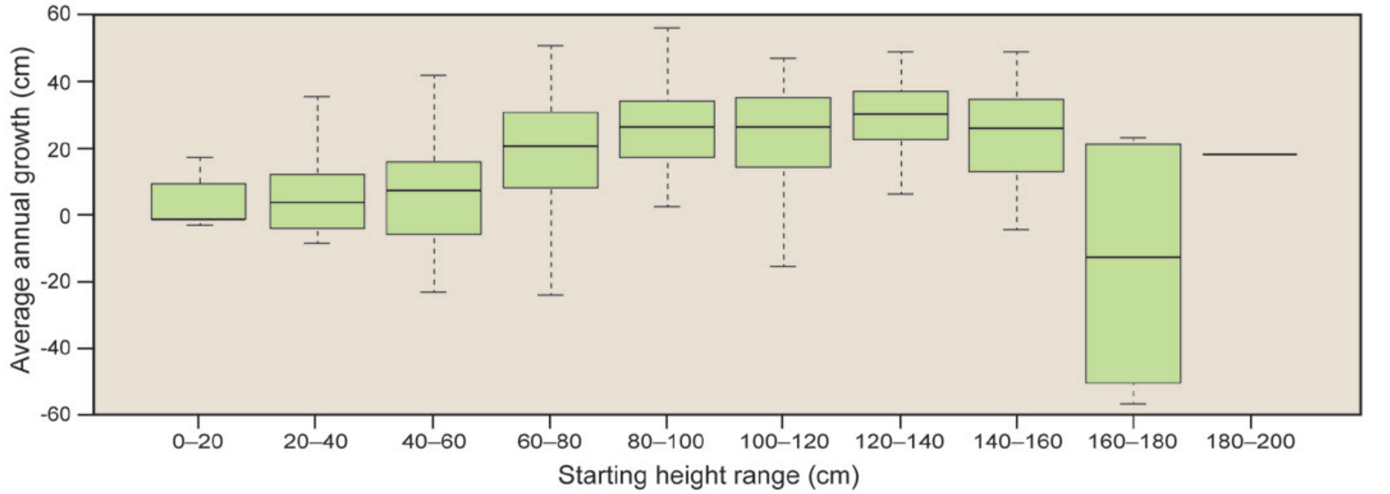

Figure 7. Median annual height growth averaged for all trees planted in a southwestern Michigan wetland from 2011 to 2020 and grouped by initial height class at planting. Starting height classes are in increments of 20 cm median height class.

Hydrology

Pools excavated at the study site displayed a range of hydrology types, ranging from consistently wet to relatively dry with water levels consistently below the soil line (figure 8). Wet pools had depths as high as 10 in (25 cm), while the driest pools were as low as 10 in (25 cm) below ground level. Pools also had high variance (water heights that varied from extremely high to low) and low variance (water heights that were stable) (figure 8). Most pools had water levels from 2 to 7 in (5 to 18 cm) below the soil surface most of the year. In general, hydrological variables were only weakly correlated with 3-year tree-growth parameters (table 4). Most species preferred drier microsites, indicated by negative coefficients for water height (especially during summer) and positive coefficients for the number of days with water greater than 10 in (25 cm) below the soil surface. These data indicate that a high water table in summer was associated with growth reductions. Eastern white pine, balsam fir, and white spruce growth rates

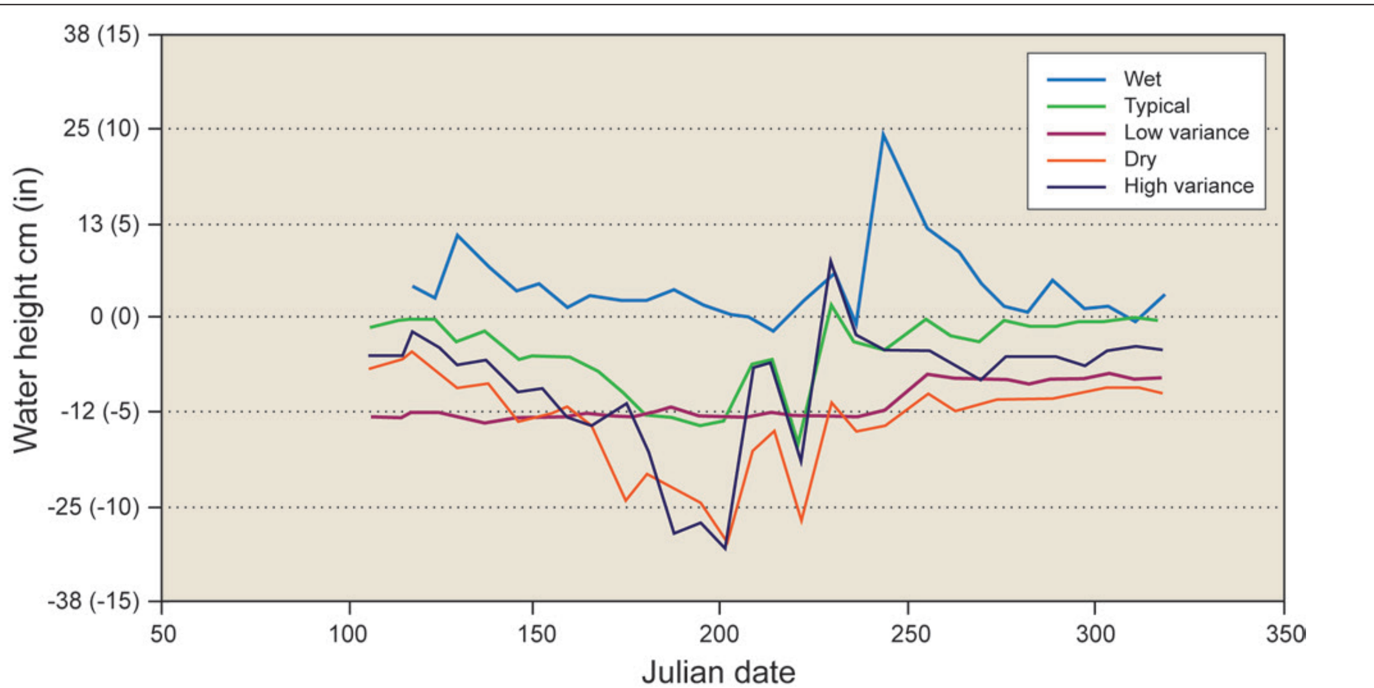

Figure 8. Water table height for five representative pools measured weekly in 2020. This graph shows pools with consistently high water tables (wet), consistently low water tables (dry), and a typical pool. In addition, some pools exhibited low variation in water depth while others exhibited high variance over the season.

Table 4. Kendall's rank correlation coefficient between 3-year growth for a subset of species and variables with p-values for significance in parentheses (NS=nonsignificant).

Species	Common name	Mound[a]	Within 3 years of planting[b]	Median water height[c]	Mean water height[c]	June-August median water table height	Number of days water height 0–5 in below soil	Number of days water height 5–10 in below soil	Number of days water height >10 in below soil
Abies balsamea	Balsam fir	0.11 (<0.01)	0.03 (NS)	-0.09 (<0.01)	-0.10 (<0.01)	-0.10 (<0.01)	-0.07 (<0.05)	-0.02 (NS)	0.11 (<0.01)
Juniperus virginiana	Eastern red cedar	0.08 (NS)	0.01 (NS)	-0.09 (<0.05)	-0.09 (NS)	-0.08 (<0.10)	-0.10 (<0.05)	0.11 (<0.05)	0.15 (<0.01)
Picea glauca	White spruce	0.10 (<0.01)	-0.17 (<0.001)	-0.01 (NS)	-0.01 (NS)	-0.01 (NS)	-0.08 (<0.05)	-0.05 (<0.10)	0.04 (NS)
Picea mariana	Black spruce	0.16 (<0.01)	0.01 (NS)	-0.17 (<0.001)	-0.18 (<0.001)	-0.18 (<0.01)	-0.15 (<0.01)	-0.04 (<0.010)	0.20 (<0.001)
Pinus strobus	Eastern white pine	0.13 (<0.01)	0.01 (NS)	-0.02 (<0.01)	-0.10 (<0.01)	-0.11 (<0.01)	-0.09 (<0.05)	-0.05 (NS)	0.13 (<0.01)
Thuja occidentalis	Northern white cedar	0.03 (NS)	0.11 (<0.001)	-0.07 (<0.01)	-0.08 (<0.01)	-0.10 (<0.01)	-0.06 (<0.01)	-0.02 (<0.10)	0.12 (<0.01)

[a] Mounds were artificially created; positive values mean growth was favorable on mounded versus unmounded sites.

[b] Positive values indicate growth of trees planted within 3 years was relatively high, while negative values indicate that growth was relatively low.

[c] Negative values for water height indicate that tree growth was higher under lower water conditions.

were correlated significantly and positively with mounding. Lastly, young northern white cedar trees (less than 3 years since planting) were positively associated with high growth. In contrast, white spruce trees that were within 3 years of planting showed reduced growth (table 4).

Soil and Water Temperatures

Soil temperatures during the 2020 growing season were consistently colder than ambient temperatures. Temperatures varied depending on depth and location (figure 9). The warmest temperature recorded in lowland soil at a depth of 3 in (8 cm) was 78 °F (25.6 °C) in 2020. Conversely, the warmest soil temperature at a depth of 3 in (8 cm) on upland forested soil with a

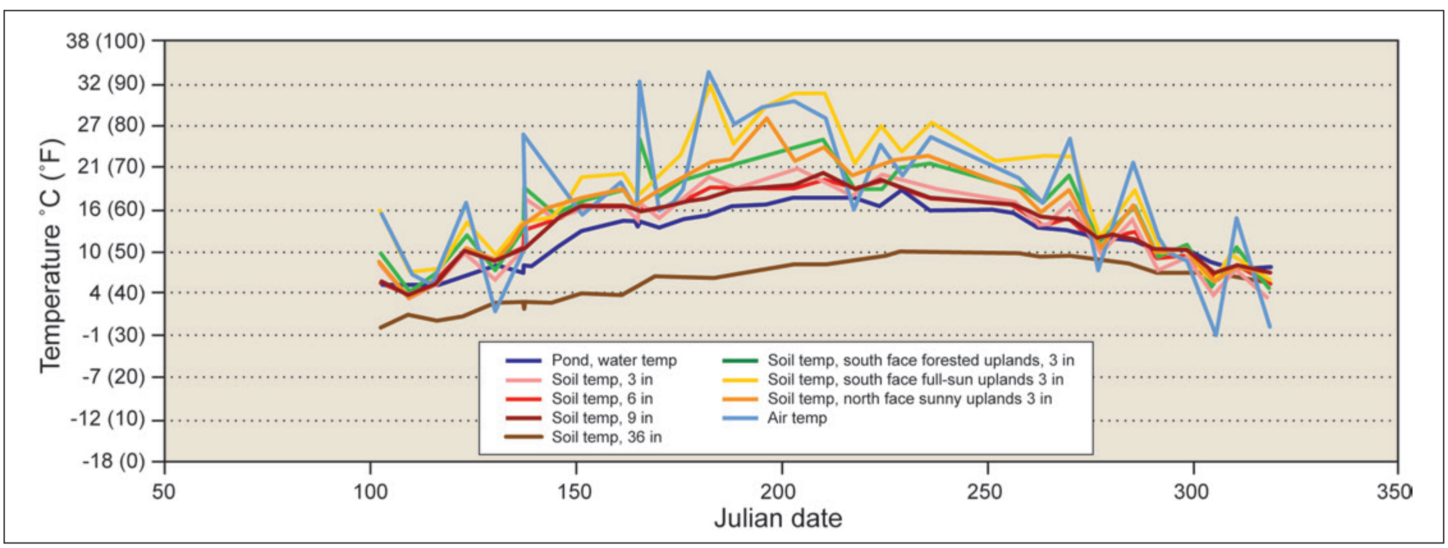

Figure 9. Temperatures (temp) were measured weekly during the 2020 growing season at multiple locations within the planting site, at varying soil depths, and in a nearby pond.

southern aspect reached 85 °F (29.4 °C). On non-forested (fully exposed) upland soils, temperatures reached 90 °F (32 °C) at 3 in (8 cm) deep. Water temperatures in the pools remained cool, with warmest temperatures ranging from 60 °F to 65 °F (15.6 °C to 18.3 °C) which was cooler than the "cold" treatment reported in Holland et al. (2003).

Discussion

The purpose of this observational study was to explore potential management options for converting a *Typha*-dominated wetland to a coniferous swamp. The benefits of a conversion include reducing methane outputs (from *Typha* decomposition), increasing carbon fixation, controlling water levels, and creating a more biodiverse ecosystem. Observations on subsequent performance of planted trees from a variety of species are aimed at providing baseline information that can be used for establishing tree cover on a converted wetland. This project also demonstrated the water table variability of these types of sites.

Variations Among Species and Seed Sources

Northern white cedar had the most annual height growth of the species studied, which was not surprising because this species is well matched to these sites (Johnston 1990). Six years after planting, many of the northern white cedar trees were taller than 96 in (244 cm). Trees planted in in 2013 had a median height of 118 in (300 cm) in 2020. This growth rate is much faster than this species generally grows in the wild, where trees often take 30 years to reach 118 in (300 cm) (Rooney et al. 2001). Relative growth rate of this species slowed as trees became larger but was still more rapid than that of other species, except eastern white pine.

Planted species were native to Michigan (balsam fir, white spruce, and black spruce) south of their typical range limits. Hydric conditions at the site were wetter than optimal, especially for seedlings that were reared in nurseries where water levels are controlled. Foliar diseases on balsam fir were observed on nursery stock. White spruce, an upland boreal species, eventually became established but likely experienced transplant shock in the first 3 years after planting. The need to replant white spruce decreased considerably in later years, suggesting the species was able to adapt its root system to various soils as found previously (Strong and La Roi 1983). Black spruce, commonly found in lowlands, had high survival and was relatively competitive on the site in spite of being moved southward. White spruce and black spruce grew faster than might be expected along their southern range edge and may have benefitted from the site's longer growing season compared to more northerly sites. While it is possible climate-related issues may not be observed until these trees are older, tree adaptation to warmer temperatures has been observed (Bermudez et al. 2021). Forest managers may seek out similar sites, with northerly aspects and cold microsites, to manage as reservoirs to maintain northern species on the landscape even as the climate warms.

Although Atlantic white cedar and pitch pine (*Pinus rigida* Mill.) were moved far west of their natural ranges, growth rates for both species were higher than expected. The seed source for Atlantic white cedar was poorly matched to the local climate (New Jersey versus Michigan), but the species typically thrives in high water tables (Golat and Lowry 1987). Atlantic white cedar had only minor cold damage and grew surprisingly well considering the stock type was younger than other species. These observations suggest that more inland habitats might be possible to conserve Atlantic white cedar populations that are otherwise largely coastal and in areas with dense anthropogenic pressure. Limited research exists on the establishment of this species even in the warmer part of its commercial range in the Carolinas (Hinsley et al. 1999). Pitch pine thrives in a climate warmer than hard pines native to Michigan and is also reported to grow in swamps alongside Atlantic white cedar. Pitch pine may be adapted to future warmer climates as demonstrated by successful regeneration through seeding in sand dunes in Ottawa County, MI (Reznicek et al. 2011).

Cold Damage

Some cold damage occurred on the nonnative trees which appeared as frost heave and/or damaged needles. Frost heave was generally only a temporary setback for the nonnative species (white fir and Atlantic white cedar), and negative growth rates were not frequent enough to have a notable effect on median growth. For Sitka spruce, needles became necrotic on some trees over the winter and were dropped in the spring. After

10 years, only 39 of the 103 planted Sitka spruce survived, nearly all of which experienced periodic foliar loss (mostly during the few years after establishment). The Sitka spruce originated from a coastal Washington seed source (plant hardiness zone 7 versus zone 5 for Michigan). White fir also exhibited slow growth, similar to native balsam fir, which wasn't unexpected since neither species are considered wetland specialists.

Variations Among Stock Types

Because researchers planted a wide variety of stock types and seed sources, the ability to recommend specific stock types and seed sources is limited. Most of the stock types were larger than those typically used for upland plantings (e.g., 2-2 compared with 1-0 or 2-0 stock types). These larger stock types are less economical but were expected to fare better under heavy competition at the site. Based on results from this study, stock types with heights of 24 to 47 in (60 to 120 cm) are recommended for similar wetland tree plantings. Tree seedlings in this size range showed better survival and were easier to transport and plant than those that that exceeded 47 in (120 cm) in height. Small seedlings were at a competitive disadvantage, while trees that exceeded 60 in (150 cm) experienced notable transplant shock.

Typha Removal

Typha spp. dominated this previously forested stand and were present in high densities (approximately 100 stems per yd^2 [120 per m^2]). The labor costs to remove stems mechanically from the entire area were prohibitive, so *Typha* was removed from two small plots as a pilot study. Shade-tolerant trees, such as northern white cedar and balsam fir, established successfully on plots without *Typha* removal, which is a desirable finding for private landowners with limited resources. Hovik and Reinartz (2007) reported a positive effect of removing reed canarygrass on tree growth, although the rooting habits of reed canarygrass and *Typha* are likely different.

Mounding

Mounding, as a strategy to create dry microsites in otherwise wet sites, was beneficial to some species, such as white spruce, in this study and in other studies (Hawkins et al.1995, Londo and Mroz 2001, McMinn 1983, McMinn et al. 1995). For other species, such as northern white cedar, no benefits of mounding were observed, which contrasts with Mehne and Mehne (2014) on the same site. Based on these contrasting results, additional data are needed to compare long-term survival and growth on mounded and unmounded microsites for conifers on these wetlands. Nonetheless, mounding may be helpful to create upland microsites in extremely hydric conditions. Well-decomposed mud, along with a mound size of about 1 gal (4.5 L) of mud per 1 ft (30 cm) of tree height, were observed to be optimal for tree growth.

Management Implications for Conifer Swamps

One of the landowner's management goals for this study site was to shade out invasive species. Observations suggest that the planted trees are becoming established in spite of the challenging hydrological conditions. Some of the first northern white cedar planted in 2002 (prior to the current study) have grown enough to begin shading out invasive *Typha* species. Sufficient shading may have occurred sooner if trees had been planted 4 ft (1.2 m) apart rather than 8 to 9 ft (2.4 to 2.7 m). Once northern white cedar was established, other shade-tolerant (and markedly more aggressive) shrubs such as red osier dogwood (*Cornus sericea* L.) also became established and appeared to outcompete *Typha* spp. If the planted trees continue growing at their current rate, approximately 70 percent of the study area will be shaded in another 5 to 7 years, which is about 20 years from the time of planting until canopy closure.

The study site was typical of conifer wetlands in the Midwestern United States, with high annual variability in hydrology. A relatively weak influence of hydrology on tree growth (table 4) may be due to uneven sample sizes, variable water, or other factors. Some trends were apparent, however. The length of time a given area remained wet was a better predictor for species performance than whether the area experienced pulses of extreme wet or dry conditions. Recommendations for land managers include evaluating planted trees at different times of the year, particularly in the summer when the water table is presumably at its lowest point, as well as monitoring across multiple years to make a complete determination on the planting's success or failure.

The cost to establish trees in the study was approximately four times the cost of tree planting on an optimal upland site due to the larger stock used and the labor required. When the recommendations from this study were repeated on a small-scale (<1 ac [0.4 ha]), followup planting, the cost was 2.7 times the expected cost for an optimal upland planting, which could be logistically feasible in some scenarios.

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Deep-Root Strategies for Propagating and Planting Seedlings for Arid Sites

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Abstract

Establishing trees and shrubs in arid and semiarid lands is difficult. With climate change and more severe droughts, the challenge will increase. Developing strong, deep roots will often improve survival. Wick irrigation can minimize water use for tall containers in the nursery and increase water availability in the field.

Introduction

Despite the increasing recognition of the global impacts of drought and desertification, revegetation in arid and semiarid environments has not been extensively studied. Extreme temperatures, intense solar radiation, limited moisture, and the low fertility of desert soils combine to make natural recovery of these areas very slow after disturbance. One key to improve seedling establishment and success is the use of tall containers (Bainbridge 1987, 2007; Dreesen and Fenchel 2014; Rodgers 1994). In addition, water delivery during establishment could further increase outplanting successes.

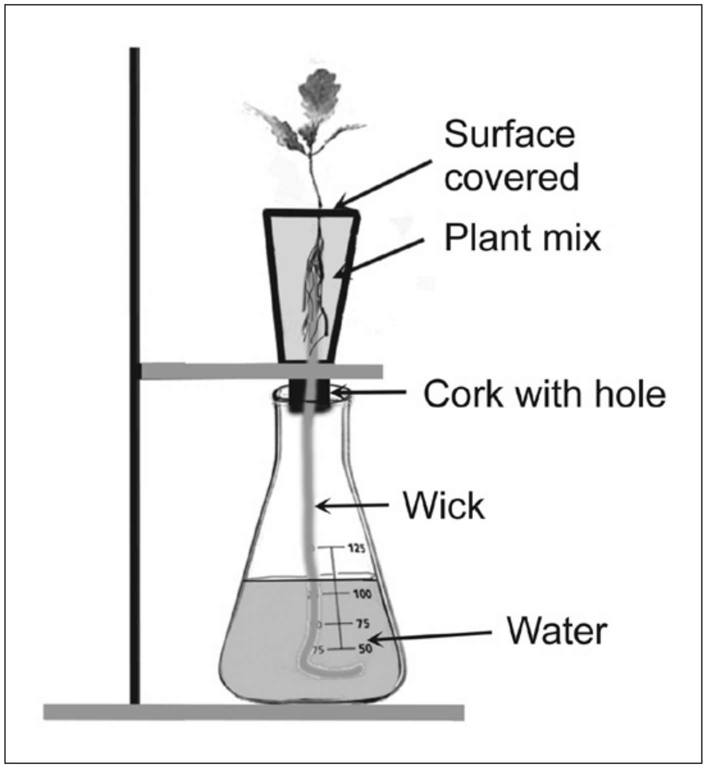

Figure 1. Simple wick irrigation has been researched in water efficiency trials.

Improving field survival with minimal water use is challenging. Wick irrigation has been used in greenhouse water-use studies (figure 1), and interest in its use for greenhouse and field applications has grown (Berkelaar 2012, Junejo et al. 2022, Kamalam 2016, Semananda et al. 2018). Yeager and Henley (2004) showed that capillary wick irrigation systems reduced water use an average 86 and 81 percent when compared with overhead and capillary mat irrigation, respectively.

A traditional Indian system that combined buried clay pots and wicks for tree planting (figure 2) (Mari Gowda 1974) inspired tests of wick irrigation (Bainbridge 2001). The first proof of concept was growing a blue paloverde (*Parkinsonia florida* [Benth. ex A. Gray] S. Watson) seedling in a container of 16-grit silica sand with a capillary wick from a reservoir below the container. This seedling grew well with water consumption of just 20 to 30 ml/day. The second field test used vertical 9-mm wicks rising from an inverted 7.5-cm buried drainpipe filled from a standpipe at one end (Bainbridge and Virginia 1989). This method improved survival, but the 9-mm wicks failed to provide sufficient water when temperatures soared. A later experiment used solid-braid nylon rope (50-cm long, 11-mm diameter, and washed in hot water with detergent) as

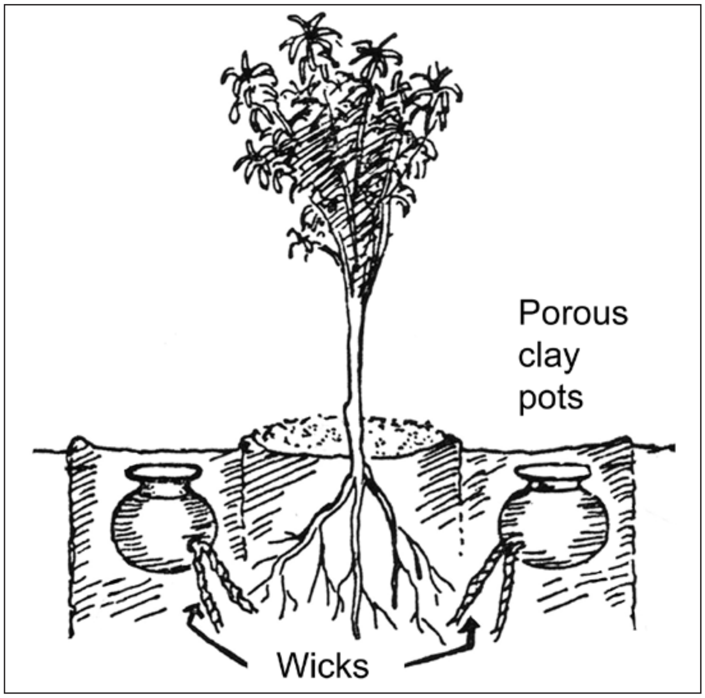

Figure 2. An early study using clay pots and wicks inspired additional research. Adapted from Mari Gowda 1974.

the wick (Bainbridge 2012) for mesquite (*Prosopis juliflora* [Sw.] DC.) seedlings. The wick was covered with a vinyl sleeve and ran from an 8-L water reservoir to the soil at each seedling. After receiving less than 120 L of water per plant (and less than 7.5 cm of rain), all mesquite seedlings were alive and well after 3 years.

The success of gravity wicks led to consideration of bringing wicks together with tall containers. This combination would minimize water use and encourage taproot development in the nursery. The wick could also be connected to a water supply in the field after the seedling is planted.

Wick Irrigation for Tall Containers

Initial tests of wick flow rates in tall containers used blue food coloring to track the wetted area of the wick. The wetting rate for gravity flow in washed, 11-mm solid-braid nylon rope (Lehigh Group, Macungie, PA) was 6 cm/min. Capillary rise reached 45 cm after 24 h. In October 2021, the author built a jig to hold the wicks in the center of a Treepots™ container (TP430, 10 cm wide and 76 cm tall; Stuewe & Sons, Inc., Tangent, OR) (figure 3) and then set up one container with a cork oak (*Quercus suber* L.) acorn and one with a willow (*Salix* spp.) cutting. Both did very well with water use of less than 250 ml/week. The acorn sprouted

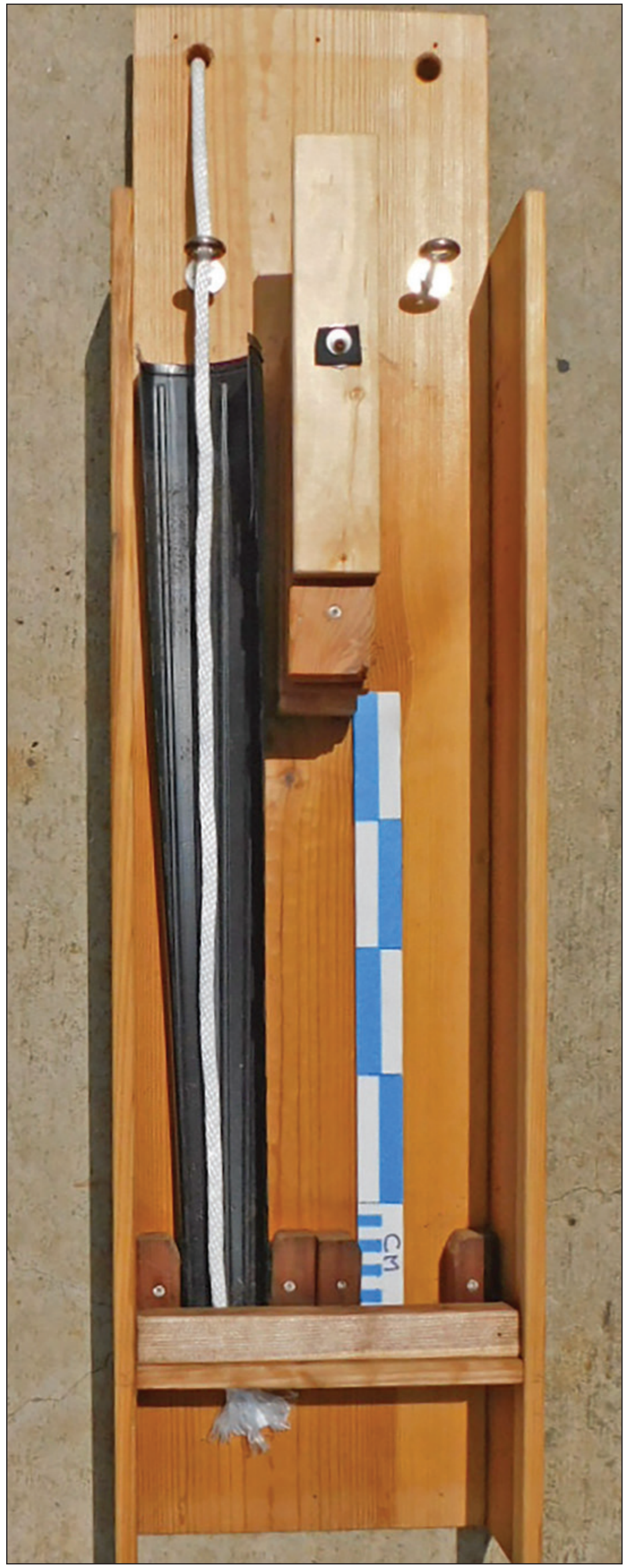

Figure 3. To study the use of wick irrigation in tall pots, the author built this jig before planting oak and willow to evaluate their performance. (Photo by David Bainbridge)

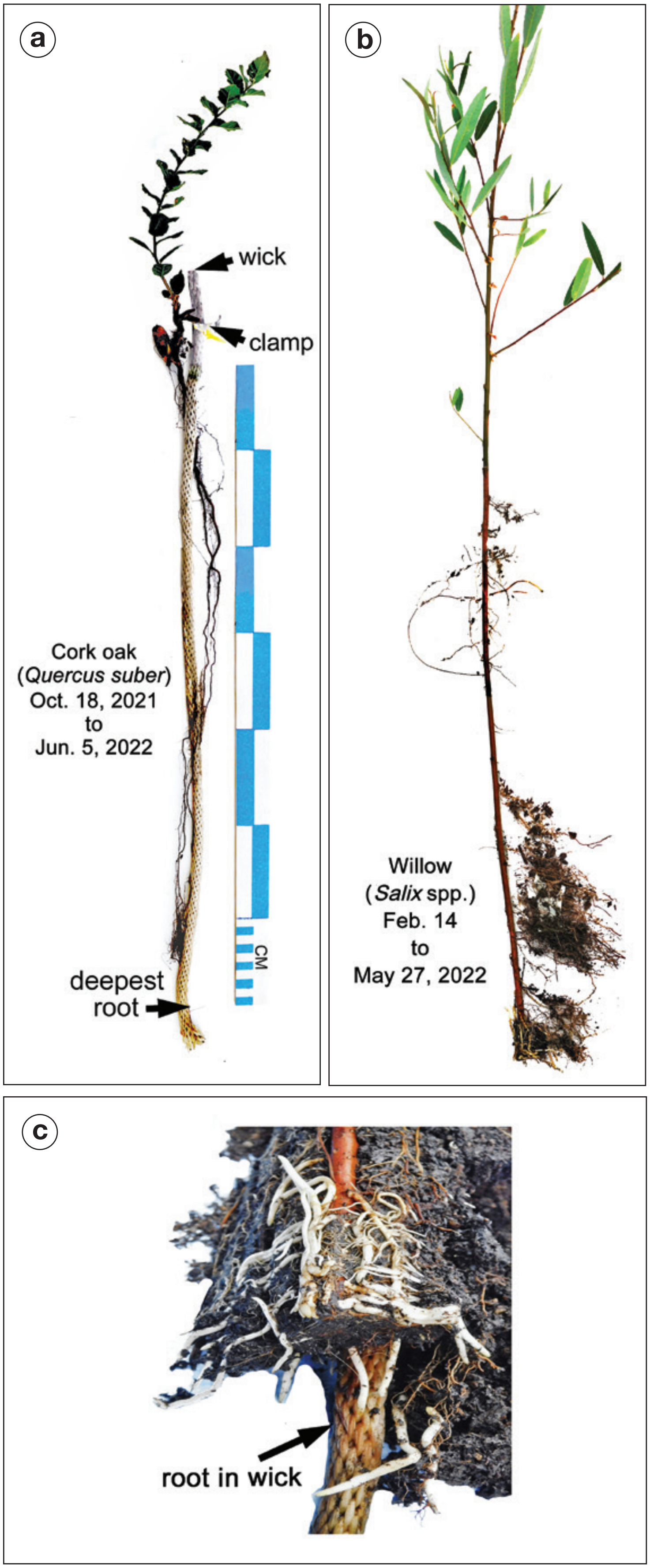

Figure 4. Growth and root development of (a) cork oak and (b) willow seedlings were excellent using wick irrigation in a tall pot. In fact, (c) roots grew near and through the wick.

and grew well. The root development was excellent, and roots were even integrated in the wick (figure 4), suggesting these seedlings would do well in the field. This method may result in robust seedlings that would be less easily damaged during transport or planting. Studies with much larger numbers of seedlings are needed (two are better than none in this case), but 100 or 200 would be better.

Research is needed to determine the best wicks and wick systems and to more fully evaluate the most appropriate uses of capillary and gravity-fed wicks. One possibility is that a wick would enable plants, cuttings, and pole plantings to reach groundwater with the combination of gravity and capillary rise (figure 5).

Deep Roots for Successful Dryland Tree Planting

Plants for drylands often depend on deep roots to endure droughts (Bainbridge 1987, Stone and Kalisz 1991). Living roots of mesquite and camel thorn (*Vachellia erioloba* [E. Mey.] P.J.H. Hurter) have been found more than 50 m deep (Canadell et al. 1996, Phillips 1963). Many dryland-adapted species

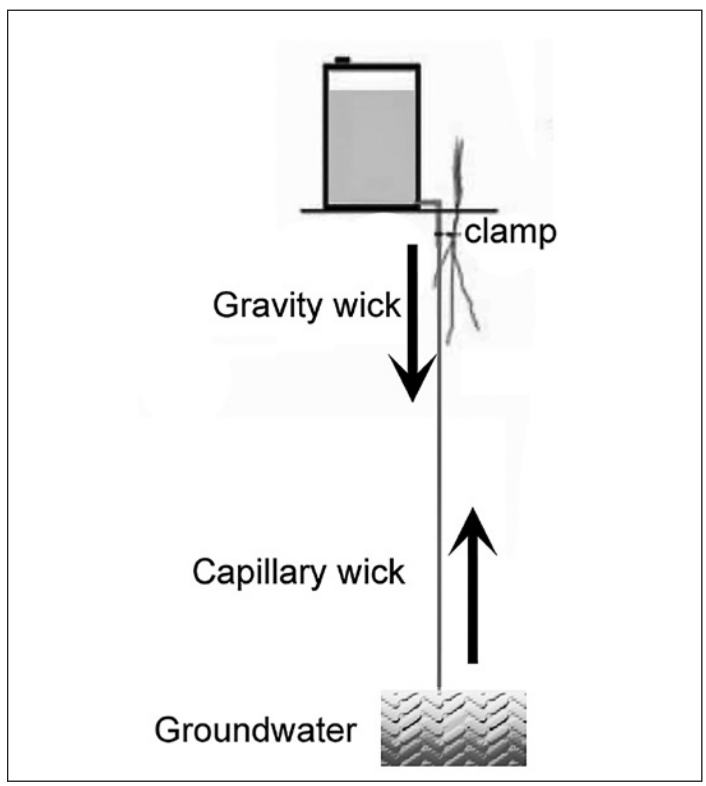

Figure 5. Wick irrigation has potential to enable access to groundwater to support plant establishment and growth.

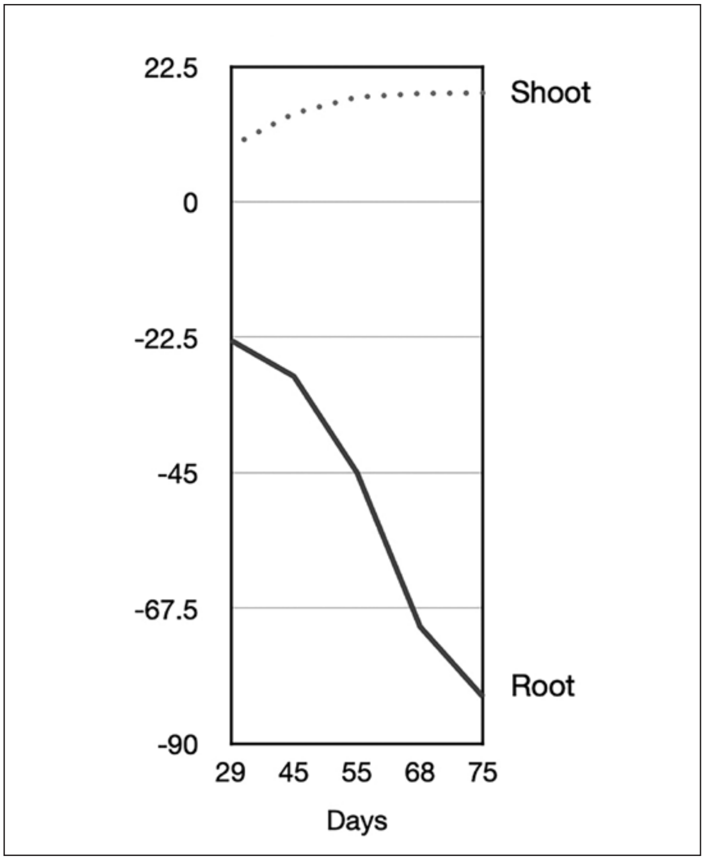

Figure 6. Dryland plants (e.g., *Parkinsonia florida*) often have rapid development of root systems relative to the shoot.

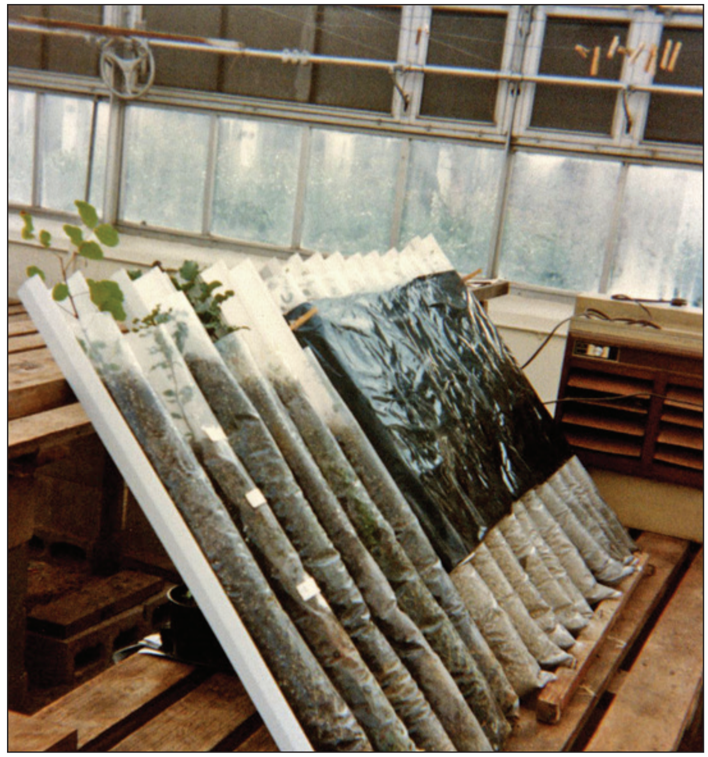

Figure 7. Plastic tubes can aid researchers in observing root development of dryland plants. (Photo by David Bainbridge)

are hard seeded and rely on flood events or artificial means for scarification and subsequent germination. The developing seedling taproot must then keep up with the soil's drying front. The rate of taproot growth for these species can be quite impressive and highlights the need for tall containers. A velvet mesquite (*Prosopis velutina* Wooton) root grew 51 mm in 12 h at 32.5 to 34.0 °C (Cannon 1917).

The pattern of root and shoot development in dryland trees and plants is often very conservative, with root-to-shoot ratios of 5:1 or much higher (figure 6). For example, 2.5-cm-tall seedlings may have roots 100 cm deep. Root growth can be assessed using 6-ml polyethylene plastic tubes (ULine, Pleasant Prairie, WI) filled with a growing medium and laid in a steeply inclined gutter section (figure 7). Observing root-growth rates can be very instructive and help determine the preferred medium and moisture for container production.

Protecting and encouraging taproot development for many dryland species in the nursery demand tall containers. When planted in areas with deep sand or soil (no caliche layer), plants grown in tall containers have improved survival compared with those grown in shorter containers (Bainbridge 2007). A wide variety of tall containers have been used with success, such as 15- by 81-cm pots at Joshua Tree National Monument (now Park) native plant nursery at Twentynine Palms, CA (Rodgers 1994) and 10- by 100-cm slit pipes developed at the Los Lunas Plant Material Center at Los Lunas, NM (Dreeson and Fenchel 2014). Treepots™ (figure 8) come in a variety of sizes and are easy to work with at relatively low cost. Taproot-dominant plants do not need a very wide container. Narrow containers also take up less space, use less planting media, and are easier to handle than wider containers.

Planting holes for seedlings grown with deep roots can be dug by hand or powered auger. A tractor-mounted auger is recommended. Outplanting should include addition of soil from healthy plants in the area to the planting hole to encourage colonization of beneficial mycorrhizal fungi (Allen 2007) and nitrogen-fixing rhizobial bacteria to help plants access water and nutrients. Woody legumes are a major source of nitrogen in many dryland ecosystems (Bainbridge 2007). Early investigators found

Figure 8. Treepots™ work well for production of deep-rooted plants to be outplanted to dry sites. (Photo by Laurie Lippitt)

few or no nodules while excavating the surface root systems, but deep drilling demonstrated that active nodules were common in deep soil (3 to 7 m) in the vadose zone just above the water table (Virginia et al. 1986). Root-eating nematodes have also been found at equally great depths (Freckman and Virginia 1989). Considering the deep-soil ecosystem in outplanting studies is important.

Further studies of deep-root development and deep-soil ecosystems are needed including development after outplanting from tall containers with and without wick irrigation. Such studies require labor-intensive excavation. Water jets can sometimes work better than shovels. Roots can also be studied with minirhizotrons (cameras that fit down clear tubes), dye, radioactive tracers, and more (Maeght et al. 2013).

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