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

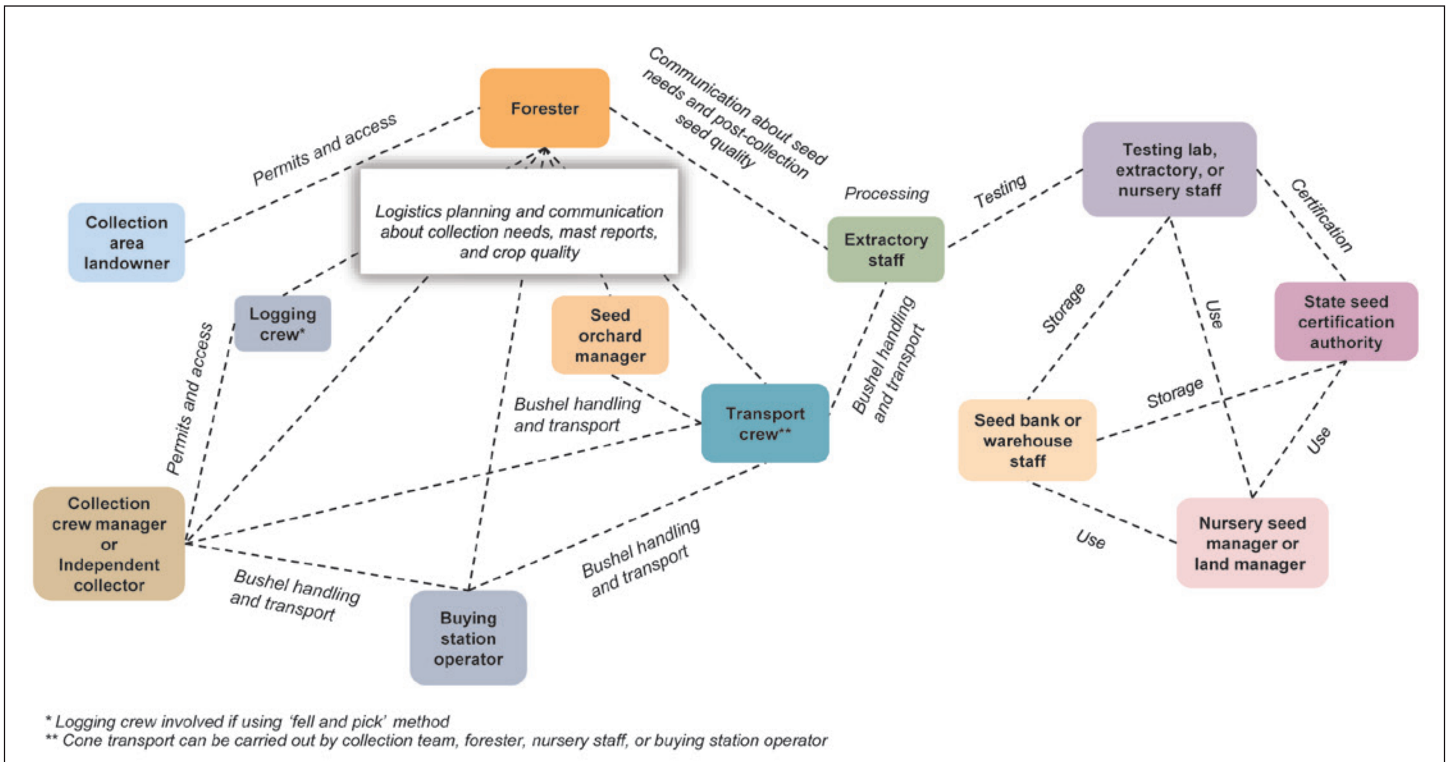

Figure 3. Stakeholder interactions along the tree-seed supply chain are critical to ensure efficiency and success. Boxes represent different stakeholders, dashed lines indicate communication or coordination needs between them, and line labels correspond to the processes or actions involved.

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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