RESEARCH ARTICLE

Integrating Science and Management to Improve Seed-Based Restoration

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ABSTRACT

Native plant seed can be used to restore healthy, resilient ecosystems in an era of global degradation and change. In the United States (U.S.), federal agencies bolster the availability of native seed by coordinating seed collection, agricultural production, and use in restoration and reclamation with a broad network of federal and non-federal partners. As a result, the native seed supply has greatly expanded, but challenges and knowledge gaps remain for effective native seed development and use. To address these issues, we synthesize lessons learned from 20+ years of experience across federally organized native plant programs engaged in developing and using native seed. We then identify strategic research directions that can help ensure that restoration can meet challenges imposed by future land disturbance and other stressors. We focus on the Bureau of Land Management Ecoregional Native Plant Programs, which began in the early 2000s to address growing demand for native seed. Our synthesis reveals that sustained partnerships can help connect a complex network of land managers, researchers, and seed growers to develop seed resources, guidance, and decision-support tools. Partners' experiences illuminated knowledge and technology gaps that constrain our abilities to maintain ecosystem resilience. However, integrating identified research themes into restoration treatments and native seed production could help address uncertainties in native seed production and use. The lessons learned and research directions described here can provide a basis for future research and collaborative management to enhance seed-based restoration efforts in the U.S. and beyond.

Keywords: National Seed Strategy, partnerships, seed production, seed transfer

Native plants are an essential component of healthy, resilient, and functioning ecosystems. Native plant communities buffer against extreme weather events and natural disasters, safeguard water and food supplies, enhance wildlife habitat, and sequester carbon among other ecosystem services (Gann et al. 2019). Widespread degradation from land use, invasive species, altered fire regimes, aridification, and other sources threaten native plant communities and the services they provide, prompting the need to recover ecosystems via reclamation, rehabilitation, and ecological restoration (hereafter "restoration," Gann et al. 2019, NASEM 2023). The United Nations declared 2021–2030 the Decade on Ecosystem Restoration in response to the need to recover natural ecosystem biodiversity and function from widespread degradation (United Nations General Assembly 2019). Native plant materials (seeds, cuttings, and other tissues used for propagation; hereafter "native seed") can be used to restore functional ecosystems (Gann et al. 2019, Pedrini et al. 2020). However, in many countries, native seed from relevant species and within-species sources are not available in the quantity or quality needed to support restoration efforts (Pedrini and Dixon 2020, Pedrini et al. 2023).

The U.S. has made progress to increase the availability of native seed (NASEM 2023) and conduct research to inform ecological restoration at the scale of federal

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Restoration Recap

- We synthesize lessons learned and future research directions resulting from long-standing federal native plant programs supporting the National Seed Strategy for Rehabilitation and Restoration in the U.S.
- Close collaboration among land managers and researchers has resulted in science-based guidance and decision-support tools for seed selection, seed production, and new strategies for ecological restoration and reclamation.
- Future research directions aim to address seed sourcing approaches, incorporate climate variability and ecological community interactions into research and practice, compare seed production and restoration techniques, and develop decision-support tools to facilitate science-based management.
- Restoration research and practice could benefit from monitoring outcomes with standardized protocols, nationally coordinated data collection and storage, and sustained synthesis of new information to continually update best management practices.
- Federal native plant programs provide science and tools available to partners across organizational scales and a blueprint for interdisciplinary collaborations to improve native seed development and use.

land management (Shen et al. 2023). These efforts were accelerated by a Congressional mandate in 2001 urging the U.S. Department of the Interior (hereafter "Interior") to increase the supply and use of native seed for post-fire emergency stabilization and long-term rehabilitation (107th Congress 2002, NASEM 2023). In response, the Interior Bureau of Land Management (BLM) established three Ecoregional Native Plant Programs (hereafter "BLM Ecoregional Programs") between 2001 and 2016. Concurrently, the Plant Conservation Alliance, a collaboration among U.S. federal agencies and non-federal cooperators, initiated a long-term program for native seed development (NASEM 2023). One product of the Plant Conservation Alliance was the National Seed Strategy for Rehabilitation and Restoration (hereafter "Seed Strategy," PCA 2015). The Seed Strategy leveraged federal and non-federal partnerships and interagency collaboration to outline goals, objectives, and actions to ensure a reliable supply of native seed for restoration (PCA 2015). Broad progress to meet Seed Strategy goals highlights how legislative mandates have not only facilitated seed research, development, and use within U.S. federal agencies (PCA 2021, 2022, 2025), but also how federally funded efforts have supported the growth of local and regional seed networks that extend the impact of the Seed Strategy to lands managed by private, state, tribal, and other stakeholders (PCA 2021, NASEM 2023).

Despite progress, a 2023 report by the National Academies of Sciences, Engineering, and Medicine—*An Assessment of Native Seed Needs and Capacity for Their Supply*—concluded that the native seed supply in the U.S. was inadequate to meet growing restoration demands (NASEM 2023). The report recommended that advancing the Seed Strategy and improving the native seed supply chain required increasing research efforts, nurturing collaboration, and expanding the network of regional native plant programs/partnerships (NASEM 2023). In response to these recommendations, a team of U.S. Geological Survey (USGS) researchers and BLM program coordinators (hereafter "project team") convened to 1) assess the research and knowledge-gathering that has contributed to the current native seed development knowledge base, and 2) identify research needs important for supporting the next steps in implementing the Seed Strategy. The project team focused on the BLM Ecoregional Programs (Figure 1) because of their role in coordinating restoration and research efforts, generating tools and products to help recover degraded ecosystems used by stakeholders across scales, and bolstering the use and development of native seed in land management. While the BLM Ecoregional Programs are currently limited to the western U.S., the experiences of program staff and supporters can inform native seed development in other parts of the U.S. and around the world. To synthesize the knowledge gained from these programs, the project team conducted semi-structured interviews with BLM Ecoregional Program coordinators and science advisors and then convened a three-day virtual workshop with land managers and researchers from Interior, the U.S. Department of Agriculture (USDA), non-profit organizations, and universities. We acknowledge that many voices and perspectives are critical for coordinating and executing a long-term strategy to bolster landscapes dominated by healthy and resilient native plant communities. Herein, we contribute to the dialogue by 1) synthesizing lessons learned after 20+ years of coordinated research effort from BLM Ecoregional Plant Programs, and 2) identifying research to support existing and new native seed development programs.

Methods

BLM Ecoregional Plant Programs

The current BLM Ecoregional Programs are the Great Basin Native Plant Project (hereafter "Great Basin Program"), Colorado Plateau Native Plant Program (hereafter "Colorado Plateau Program"), and the Mojave Desert Native Plant Program (hereafter "Mojave Desert Program,"

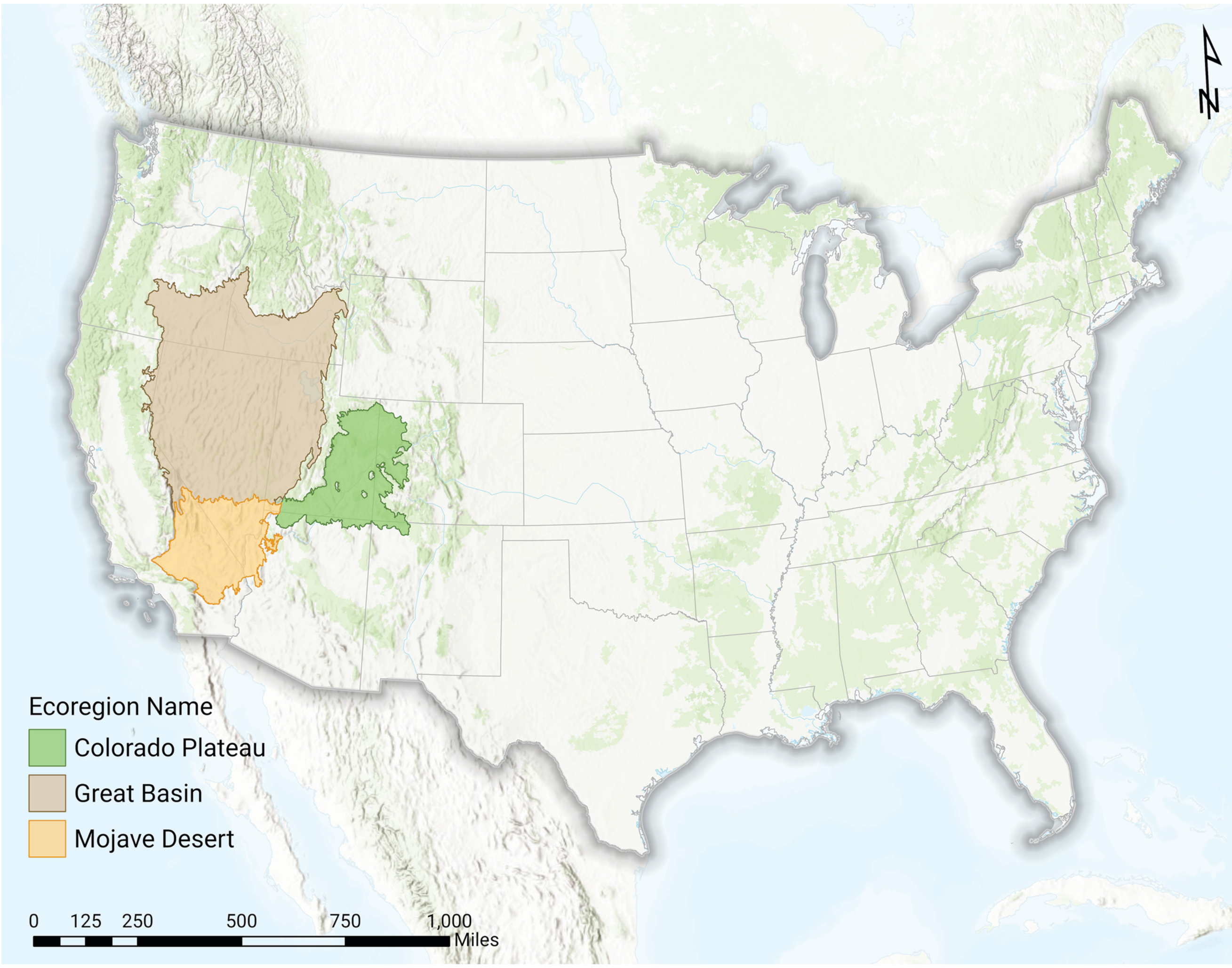

Figure 1. Map of the areas served by the Colorado Plateau, Great Basin, and Mojave Desert BLM Ecoregional Native Plant Programs. Ecoregions defined by one or more of the Environmental Protection Agency Level III Ecoregions (EPA 2024). The basemap is the World Topographic Map (Sources: Esri [2012], DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China [Hong Kong], swisstopo, MapmyIndia, and the GIS User Community).

Figure 1). These programs coordinate native seed development within their ecoregional boundaries. Native seed development is the process of selecting and collecting wild seed of native species for the agricultural production and distribution of genetically appropriate seed for ecological restoration (McCormick et al. 2021, NASEM 2023). To meet this goal, the BLM Ecoregional Programs focus on seed need assessment, seed collection, seed production, and supporting research to develop best practices and create decision-support tools for developing and using seed to restore native plant communities and ecosystems.

Semi-Structured Interviews

The project team developed interview questions to gain insight on the history of the BLM Ecoregional Programs, approaches to meeting science and management goals, relevant research findings, and challenges encountered during program implementation (Supplementary Materials 1). Two project team members conducted semi-structured interviews with three ecoregional coordinators and five researchers who conduct research in support of the BLM Ecoregional Programs; all interviewees were U.S. government employees at the time of interview and were included as co-authors of this publication. Interviews were conducted and recorded on Microsoft Teams between November 14 and December 11, 2024.

Native Seed Workshop

The project team hosted a native seed workshop to gather information from land managers and researchers who directly participate in the research informing native seed development and use, as is set forth in the Seed Strategy (PCA 2015) and supported by the BLM Ecoregional Programs. The workshop was held virtually between April 1 and 3, 2025 and included presentations on the BLM Ecoregional Plant Programs (Great Basin, Colorado Plateau, and Mojave Desert Programs), seed selection, initiating new ecoregional programs, and addressing national-level research directions (Supplementary Materials 2). The 44 workshop attendees included BLM Ecoregional Program coordinators and researchers, Plant Conservation Alliance Federal Liaisons from four Interior bureaus (BLM, USGS, National Park Service, and U.S. Fish and Wildlife Service), and other land managers and researchers from the USDA Forest Service, Interior Office of Restoration and Damage Assessment, Chicago and Denver Botanic Gardens, and multiple universities. The workshop also included an optional session to outline research directions, and workshop attendees were invited to be co-authors. Because comprehensive discussions concerning all aspects of the Seed Strategy or adjacent seed development methods such as cultivar development (Chivers et al. 2016, Shelton and Tracy 2017) were beyond the scope of this workshop, future workshops could benefit from the perspectives of seed producers, policymakers, and a broader group of researchers.

Lessons Learned and Research Directions

Overview

The project team synthesized ideas from interview transcripts and workshop notes and categorized them under three emergent themes: 1) seed selection (related to selecting species and seed sources within species), 2) seed production (related to increasing native seed through agricultural practices), or 3) restoration (related to using native seed to restore native plant communities, associated data collection, and knowledge transfer, Table 1). Within each theme, ideas from interviewees and workshop attendees (hereafter "participants") were categorized as "lessons learned" if they arose from participants' direct experiences or as "research directions and coordination directions" if they addressed scientific information gaps, new directions of scientific investigation, or methods to support effective research and communication (Table 1). We distilled research and coordination directions into action items that include improving communication and collaboration (Action 1), which, when integrated with current and future research (Actions 2–3), can be used to inform data collection, use, and synthesis efforts as best management practices for improved restoration outcomes (Action 4, Figure 2).

Sustained coordination between land managers and researchers was identified as key to conducting applied research across themes, highlighting how research-focused priorities cannot be disentangled from other goals of the Seed Strategy involving communication and collaboration. Partnerships facilitate the cross-pollination of expertise, resources, tools, and infrastructure that ensure research delivers the most relevant information for decision-support needed by resource managers (Enquist et al. 2017, Rosemartin et al. 2023). Communication sustains partnerships, and gatherings in the form of scientific and management conferences and meetings provide a venue for the dissemination of ideas and products, especially to local and regional collaborators who depend on government-funded science to inform best practices of seed development and use. Furthermore, stakeholder gatherings allow federally funded efforts, such as the BLM Ecoregional Programs, to gain feedback from non-federal partners, which helps align efforts across scales. Cohesion around a shared vision, such as the Seed Strategy's "the right seed in the right place at the right time" (PCA 2015), further strengthens and provides direction for collaboration.

Seed Selection

Seed selection choices—including choosing species, seed mix design, and within-species source selection—can influence restoration outcomes (Johnson et al. 2010, Erickson and Halford 2020, Pedrini and Dixon 2020). Participants stressed the value of seed selection tools and guidance, including priority species lists and within-species source selection guidance (Table 1). Priority species lists identify plant species of interest for research, seed source development, and use in restoration, but different approaches to their development illustrates varied visions among the three programs. One approach starts with common generalist ("workhorse") species suitable for agricultural production and focuses on specialized species later, though some participants worried that a focus on workhorse species may limit the functional diversity of the native seed available for restoration. Another approach uses an "umbrella species" concept to select priority plant species that are important to an animal of conservation concern with broad distribution across the ecoregion (i.e., *Centrocercus urophasianus* [greater sage-grouse] in the Great Basin and *Gopherus agassizii* [Mojave desert tortoise] in the Mojave Desert). The umbrella species approach can be layered with other priorities, such as pollination services (e.g., Esque et al. 2021) or the ability to compete with invasive species (Leger et al. 2014, Barak et al. 2015). Communication among partners helps develop priority species lists that meet land manager needs, but participants also emphasized the importance of regularly updating the lists in response to changing priorities and policies or new research outcomes. They also urged for flexibility when environmental conditions limit seed production of high priority species in wild populations by allowing seeds from lower-priority species to be gathered when possible. Web-based species selection tools, such as the Mojave Seed Menu tool (Shryock et al. 2022) or EcoRestore Portals (Young et al. 2025), are useful for developing seed mixes based on restoration site location and species' habitat requirements, spatial distributions, and traits that support project goals (e.g., erosion control, pollinator or wildlife habitat).

Table 1. Lessons learned and research and coordination directions described by participants within each emergent theme (seed selection, seed production, and restoration).

Theme	Lessons Learned	Research and Coordination Directions
Seed Selection	Priority species lists, co-developed by managers and researchers, guide seed collection, production, use, and research	Adapt seed sourcing guidance for projected climatic and weather trends
	Research-based guidance supports selection of appropriate species and seed sources	Compare efficacy and compatibility of seed sourcing approaches across species, space, and time
	Web-based decision-support tools incorporate available knowledge to guide prioritization of species and sources for development and use	Incorporate soil properties, community interactions, and plant traits into seed selection research and guidance
		Develop information-rich, "one-stop-shop" decision-support tools for species and within-species source selection
Seed Production	Nationally coordinated programs bolster regionally led seed collection and production efforts, which result in the timely development of new native seed sources	Increase coordination, research, and communication across the seed supply chain
		Develop production strategies for growing native plant species
	Native seed partnerships build relationships with growers to trial new seed production methods	Research and develop guidance for pooling within-species sources and minimizing unintentional artificial selection
Restoration	Collaborative manager-researcher partnerships can successfully integrate monitoring and research into restoration practice	Improve documentation of restoration practices, implement standardized monitoring protocols for restoration outcomes, and develop digital database(s) to house this information
	Retrospective research and sustained synthesis support evidence-based restoration guidance	Embed research experiments into restoration practice to inform future actions
		Research the effects of restoration techniques on outcomes to identify best practices
		Improve, consolidate, and develop decision-support tools to facilitate knowledge transfer

In addition to species selection, land managers rely on research-informed guidance to understand which seed source(s) they should use to support genetically appropriate restoration as described by the Seed Strategy (Winkler et al. 2024a). Genetically appropriate seed sourcing guidance generally assumes that plants are adapted to their local environments, and seed sources from environments that match the restoration site will increase the likelihood that plants will establish and thrive (McKay et al. 2005, PCA 2015). Participants discussed a variety of seed sourcing approaches. Empirical seed transfer zones (i.e., species-specific zones delineating discrete geographic boundaries in which seeds can be transferred, Kilkenny 2015) are developed with common garden studies or landscape genetic approaches (e.g., St. Clair et al. 2013, Massatti et al. 2018, Shryock et al. 2021, Custer et al. 2022), while generalized provisional seed transfer zones are largely based on climate and apply across a broad range of species (e.g., Bower et al. 2014). Seed transfer zones are useful for prioritizing seed collection and production efforts based on anticipated restoration needs in different geographic areas (e.g., Barga et al. 2023, Winkler et al. 2024a). Additionally, web-based decision-support tools, including the Seedlot Selection Tool/Climate Smart Restoration Tool (St. Clair et al. 2022) and Climate Distance Mapper (Shryock et al. 2018), allow seed sourcing decisions to be made using a focal point approach (Parker 1992) when seed sources are not available for every seed transfer zone (which is the typical circumstance). In other words, these tools can match available seed sources to potential restoration sites and rank them in terms of present or future climate similarity (regardless of whether they are in the same seed transfer zone), allowing managers and practitioners to make evidence-based decisions in the absence of commercially available sources from target seed transfer zones.

Participants identified several research directions that could improve seed selection guidance including expanding testing and comparison of seed sourcing strategies, incorporating community interactions and traits into seed selection research, and developing information-rich decision-support tools for both species and within-species source selection (Table 1). Seed sourcing guidance has typically relied on historical or present-day temperature and precipitation regimes, species distributions, and patterns of adaptation. However, future seed sourcing approaches will likely need to adapt to projected climatic changes

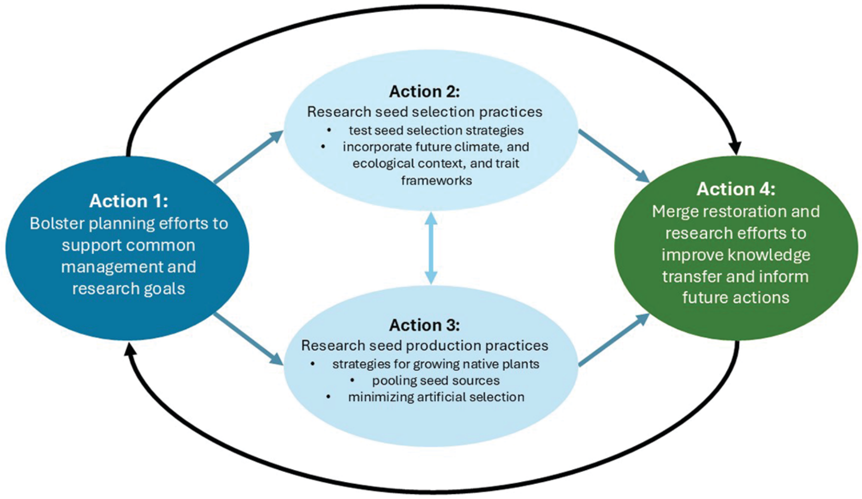

Figure 2. Summary of potential research and coordination directions for restoration programs provided by participants as discrete action items in a network representing their connections and dependencies.

(Breed et al. 2013, Havens et al. 2015, Prober et al. 2015), including warming temperatures and increasing variability in precipitation (IPCC 2021, Payton et al. 2023). Given the uncertainty of climate projections, seed sourcing guidance that accounts for future climate may need to consider a range of possible climate conditions for a given restoration site (Miller et al. 2022), including novel, non-analog combinations of climate variables (Williams and Jackson 2007). Seed sourcing approaches to account for projected climatic changes include matching seed source(s) to the predicted future climate of a restoration site (e.g., assisted gene flow, predictive/climate-adjusted provenancing, Aitken and Whitlock 2013, Prober et al. 2015) or mixing seed sources to increase genetic and phenotypic diversity (e.g., admixture provenancing, Broadhurst et al. 2008, Kettenring et al. 2014, Bucharova et al. 2019). However, non-local sourcing and mixing sources heighten potential risks including outbreeding depression, diluting local adaptation, or disrupting community interactions (Aitken and Whitlock 2013, Bucharova et al. 2019). Thorough research can be used to weigh the potential benefits and risks of these novel seed sourcing approaches and compare the effectiveness and compatibility of novel and more traditional seed sourcing approaches (e.g., seed transfer zones) across species, space, and time (Vitt et al. 2022). Research could also explore opportunities to integrate different research strategies for seed sourcing guidance (e.g., combining common garden studies with landscape genetic approaches) to expand insight and, when possible, prioritize the options available to land managers.

While climate is recognized as a strong driver of plant adaptation and serves as the primary factor in designing seed sourcing guidance (e.g., Bower et al. 2014), other factors such as soil properties, disturbance history, and ecological interactions may also influence patterns of gene flow and survival (Gibson et al. 2019, Hargreaves et al. 2020, Roybal et al. 2025). Seed sourcing approaches that do not consider these factors may lead to a mismatch between predicted environmental suitability and actual site conditions (Aitken and Whitlock 2013). Considering non-climatic environmental factors is especially important for non-local seed sourcing approaches, as both climate change and long-distance seed movement have the potential to decouple relationships between plants and other community members (Aitken and Whitlock 2013, Gornish and Tylianakis 2013). For example, climate-based sourcing approaches alone may fail if seeds are planted in areas that lack suitable soil conditions or pollinators or have herbivory/granivory pressures that were not present in their home range (e.g., Silliman 2024). In addition, conditions at some sites in need of restoration or rehabilitation may be so disturbed that the environments to which local genotypes are adapted may no longer be present; such scenarios may require alternative land management strategies such as non-local seed sourcing (Jones 2003, Jones and Monaco 2007, Chivers et al. 2016). Thus, a thorough research framework can be developed to elucidate when and how to incorporate soil properties and community interactions into seed sourcing guidance.

Participants also saw merit in incorporating trait-based approaches into seed selection research and guidance. Plant traits are measurable characteristics that mediate the relationship between genetics and the environment and influence plant responses to conditions in restoration settings (Carlucci et al. 2020). Developing a standardized set of trait measurements, prioritized by ease of measurement and generalized relevance across species (e.g., Wigley et al. 2020, Winkler et al. 2024b), could help researchers identify traits that promote establishment and fitness in a given environment (e.g., Garbowski et al. 2020, Butterfield et al. 2023) and support desired ecosystem services across variable environments (Funk et al. 2024). Additional research can also help inform strategic use of within- and among-species trait variation and plasticity to improve restoration outcomes (Kettenring et al. 2014, Espeland et al. 2018, Samuel et al. 2024). Ideally, this information could be translated into protocols for rapidly screening plant populations for traits that are adaptive to specific conditions (e.g., Leger et al. 2021) and into seed selection tools that are tested with manager-researcher partnerships.

Regular communication between researchers and managers conveys results of these identified seed-selection research directions, but manager participants also requested that information be synthesized into web-based decision-support tools. Existing seed selection tools often focus on species *or* within-species source selection as informed by climate or traits and their associated ecosystem services. Participants described the ideal seed selection tool as a "one-stop-shop" that recommends *both* species and within-species source(s) based on site conditions and project goals and that incorporates a broad range of climatic, environmental, trait, and genetic information. Specifically, the tool could:

- guide users to select the seed sourcing approach most appropriate for their species of interest, restoration site, goals, and project constraints (e.g., seed availability and budgets);
- incorporate a broad range of environmental variables including current and future climate variables, uncertainty due to extreme events and increased climate variability, and non-climatic variables such as soil properties and disturbance regimes; and
- include information on plant traits, community interactions, local adaptation, and genetic variation.

This information-rich tool could enable land managers to select species and seed sources that enhance restoration outcomes and desired ecosystem services.

Seed Production

The native seed development process depends upon agricultural practices to produce adequate seed quantities for restoration projects, thereby mitigating potential damage of overharvesting from wild plant populations (Pedrini et al. 2020, McCormick et al. 2021). This socioeconomically complex process relies on an array of partnerships and contracts involving government agencies, seed cleaning and storage facilities, agricultural growers, and seed certification agencies (NASEM 2023). Participants identified producing new native seed sources from wild seed collections as a major success across BLM Ecoregional Programs, which engage partners to collect, clean, produce, store, and distribute native seed. Specifically, the Seeds of Success (SOS) Program coordinates seed collection with science-based protocols and a network of partners (Haidet and Olwell 2015). Similarly, the BLM Indefinite Delivery Indefinite Quantity (IDIQ) production contract facilitated agricultural production of native seed not readily available on the commercial market, such as seeds from under-served seed transfer zones (NASEM 2023). Participants also acknowledged the critical role of non-federal programs, such as regional native seed partnerships (e.g., Southwest Seed Partnership, Understory Initiative, and Diné Native Plants Program), that expand upon activities coordinated by the BLM Ecoregional Programs to synergistically develop production methods and produce native seed sources in conjunction with local and regional growers at schools, universities, non-profits, and Tribal Nations. Nonetheless, participants identified increased coordination, research, and communication across the native seed supply chain as future directions for a consolidated seed development pipeline.

Participants identified future research directions to promote native seed production including analysis to project future seed demand and integration of research into the native seed production process (Table 1). Recommendations to improve the U.S. native seed supply often involve stabilizing and increasing the predictability of demand, developing species-specific production methods, mitigating the financial risk for commercial growers to try growing new species, and expanding outreach efforts to share guidance and seed resources (White et al. 2018, NASEM 2023). Participants suggested that sustained quantification of projected federal seed needs and their expected costs could guide long-term contracting and production strategies. Furthermore, practices for growing native seed in agricultural settings are not well understood; additional research can help develop production protocols for many priority restoration species (White et al. 2018). Protocols are especially important for species and functional groups that are considered difficult to grow, including annual species and species with high seed dormancy, low seed viability, or that tend to reproduce vegetatively. Seed production contracts could include research, development, and dissemination components to address key challenges of native seed production, and these contracts would ideally incorporate flexibility on delivery and timeline to reduce risks. Participants also identified the benefits of partnerships with small, local or regional growers and university agricultural extension programs to test production methods before entering into large-scale seed production contracts. Lastly, cross-sector communication and outreach with "agricultural liaisons" who understand the terminology and practice of both ecology and agriculture may help translate research results into actionable guidance to ensure economically viable and ecologically sound native seed production.

Research exploring how agricultural seed production methods affect the genetics, traits, and performance of resulting seed resources could also help inform seed production. Pooling sources from multiple populations of a species is sometimes necessary to supply growers with sufficient starting material to sow fields and has been proposed as a strategy to increase genetic variation (Bucharova et al. 2019, Erickson and Halford 2020). For instance, the BLM IDIQ production contract described above recommended pooling at least ten source populations for production. However, mixing multiple within-species sources could increase the risks of outbreeding depression and erosion of locally adapted traits (e.g., Hufford et al. 2012), especially when ploidy levels (i.e., the number of sets of chromosomes) differ among source populations (Gibson et al 2017, Kramer et al. 2018, Kaulfuß and Reisch 2019). Regardless of whether seeds are pooled or not, agricultural methods can result in genetic shifts in the harvested seed (Espeland et al. 2017), and additional research can help explore genetic impacts on restoration outcomes.

Contemporary ecological restoration guidelines from the Seed Strategy and Society for Ecological Restoration focus on producing native seed sources that have not undergone selection that could potentially limit genetic or trait diversity (PCA 2015, Pedrini and Dixon 2020). These seed sources are defined as "source identified" under U.S. seed certification labelling systems, meaning they have known geographic origin and have not undergone any intentional selection (Aubry et al. 2005, Young et al. 2006). In contrast, native seed production in the U.S. traditionally focused on creating cultivated varieties (or cultivars) that have known, heritable, uniform, performance-based traits through intentional selection (e.g., selecting populations with performance-based traits or plant breeding efforts, Aubry et al. 2005, Young et al. 2006). Some researchers have raised concerns about the use of cultivars in ecological restoration, including potential loss of genetic variation, trait uniformity, selection of agriculturally suitable traits that may not be suitable in restoration settings and native ecosystems, and competition with or genetic contamination to locally adapted plants (Kettenring et al. 2014, Leger et al. 2021, 2024). Federal agencies in the U.S., including the BLM, do allow cultivar use when source identified seed sources are not available or practical, as cultivars are often more available and less expensive than other native seed sources (Shriver et al. 2025). Additionally, some researchers suggest that intentional selection is a useful tool for developing seed sources with traits that could improve performance in degraded ecosystems (Jones 2003, Jones and Monaco 2007, Chivers et al. 2016). Participants suggested future research to investigate how widespread past and ongoing cultivar use affects restoration outcomes and potential impacts to native plant populations and wider ecosystem dynamics.

Unintentional selection during native seed development is well documented (Conrady et al. 2023) and can impact seed establishment and success (Kramer et al. 2019). Repeated cycles of agricultural production may favor traits that enhance production efficiency (e.g., rapid germination, reduced seed dormancy, and uniform ripening, Leger et al. 2024), but these same traits can compromise ecological function and reduce fitness in wild ecosystems (Leger et al. 2021, Pizza et al. 2021). Additional research could clarify which factors (e.g., species traits and production techniques) and stages of native seed development most influence changes in genetic diversity and trait shifts. Lastly, participants recommended research exploring how geographic and environmental distance between seed production sites and population origin affect restoration outcomes, given that conditions in seed production fields may inadvertently select for traits that are maladaptive in the target environment (Espeland et al. 2017). Collaborative research that integrates agriculture, ecology, and genetics can inform evidence-based best practices for agricultural native seed production that support long-term restoration success.

Restoration

Every restoration project conducted by land managers holds the potential to contribute to the field of restoration science, and many managers and researchers collaborate to build collective knowledge to improve outcomes. Participants emphasized the importance of integrating management objectives with strategic monitoring of, and scientific inquiry into, restoration projects, then synthesizing outcomes to develop evidence-based guidance (Table 1). Participants were eager to incorporate data collection and monitoring efforts into restoration projects, though they noted this may be challenging for land managers with limited capacity, time, and resources, and who lack monitoring requirements or support from leadership. Sustained manager-researcher partnerships not only facilitate rapid incorporation of new science into restoration practices but also enable research experiments to be embedded into restoration projects to test manager-driven questions directly. For instance, land managers and researchers developed the Seeding Evaluation and Experimental Design (SEEDS) project that incorporates large-scale experiments into existing restoration projects and other post-fire recovery actions in the Great Basin. Bringing research resources, funding, and personnel for experimental set up and monitoring indicated that collaboration may be more appealing to land managers for the SEEDS project and similar efforts.

Retrospective and sustained analysis of existing data and on-going restoration monitoring were also considered important for developing guidance and informing future management actions. For example, the USGS Land Treatment Digital Library (LTDL) and associated Land Treatment Exploration Tool (LTET) house data from several decades of management treatments that can be used for retrospective research and synthesis studies (e.g., Copeland et al. 2018). Researchers can also use data from past experiments in published literature (e.g., Baughman et al. 2019) or collect data from restored populations, such as tissue samples for genetic analyses (e.g., Jordan et al. 2019). While one-time syntheses of existing information are useful, participants suggested recurring, sustained synthesis to provide land managers with the latest science and guidance to inform best management practices. Regional "fire science exchanges" sponsored by the U.S. Joint Fire Science Program were identified as examples of effective sustained synthesis and information delivery.

Future research directions for restoration involve merging monitoring, research, and management practices to advance effective techniques and facilitate knowledge transfer (Table 1). Regular and consistent documentation of practices employed throughout native seed development and use could help connect seed production, seed selection, and restoration choices to outcomes and costs. Important variables to document include restoration project objectives, seed collection and production practices, site characteristics and conditions, methods and timing of implementation, and post-planting management. Ideally, restoration outcomes would be documented with standardized monitoring protocols that assess pre-determined indicators of whether project objectives are achieved. To facilitate ease of use by land managers, standardized monitoring protocols would be accessible, feasible, and relevant for documenting practices and outcomes across a wide spectrum of site conditions and project types. To account for different restoration project goals and methods and the variety of ecosystems in which they occur, monitoring protocols could be presented as customizable toolkits with universal baseline metrics, which can be compared across sites and site-specific metrics. Ideally, monitoring data could be entered into and stored in accessible, nationally coordinated digital database(s) to streamline data compilation for later synthesis or to facilitate adaptive management.

Participants also identified the importance of synthesizing data from past restoration projects to develop evidence-based guidance and inform future actions. For instance, retrospective research that synthesizes information from multiple projects conducted across space and time could allow managers to separate management-driven signals from temporal and spatial environmental variability for a broader view of effective restoration strategies and knowledge gaps (Copeland et al. 2019, Shackelford et al. 2021). Contemporary research can also address research questions by embedding experiments into restoration projects (e.g., the approach employed by the SEEDS project described above, Ott et al. 2019, 2022) or through structured, hypothesis-driven adaptive management (McIver et al. 2014). As defined by the U.S. National Research Council and adopted by Interior, adaptive management is a process that promotes flexible decision making that can be adjusted as outcomes from management and restoration actions become better understood (Williams et al. 2009). Under this framework, careful outcome monitoring advances scientific understanding and helps ensure that these results inform future actions and policies as part of an iterative learning process (Williams et al. 2009). Cross-site experimental restoration networks co-developed by researchers and land managers, including the RestoreNet experiment (Havrilla et al. 2020, Farrell et al. 2023), can help determine the influence of restoration treatments across environmental settings and strengthen knowledge sharing. Additionally, adaptive management programs for invasive species management (e.g., Native Prairie Adaptive Management Program, Gannon et al. 2013, 2024; Annual Brome Adaptive Management Project, Symstad et al. 2022) provide examples relevant to restoration.

These monitoring, research, and adaptive management frameworks may be useful for testing and improving restoration methods. Effective restoration methods can be used to address stressful climatic conditions (e.g., high temperatures, prolonged drought) and climatic variability and uncertainty, all of which may compound existing restoration challenges, particularly in dryland ecosystems where seed-based restoration is already challenging (Shackelford et al. 2021). Research that explores methods that provide and enhance key restoration processes alongside science-manager interactions could improve restoration outcomes under variable conditions. For instance, participants suggested that research explore:

- the impacts of seed selection and production choices on restoration outcomes and ecosystem services;
- seeding and outplanting methods to overcome seed and seedling recruitment and survival barriers (e.g., low soil moisture, herbivory/granivory, competition with invasive species);
- ways to leverage and encourage positive plant community interactions with pollinators, seed dispersers, soil microbial communities, and biocrusts, as well as plant-plant facilitation;
- methods that combine restoration techniques and (or) expand functional diversity to bet-hedge against unpredictable climatic and environmental conditions; and
- uses of molecular tools and genetic monitoring programs to enhance our understanding of restoration in a community context.

Lastly, land managers increasingly use decision-support tools to bridge the divide between science and practice. Although many existing decision-support tools for seed-based restoration facilitate seed selection (Shryock et al. 2018, 2022; St. Clair et al. 2022; Young et al. 2025), fewer decision-support tools exist for other major stages of restoration, such as the selection of seeding or outplanting methods, accompanying restoration treatments to bolster seeding success, or treatment timing. Moving forward, decision-support tools could ideally address decisions made at each stage of the restoration process, balance overlapping and sometimes conflicting priorities, and be accessible to managers with a wide range of restoration experience. For instance, frameworks can be developed to guide managers through the processes of bet-hedging (i.e., implementing multiple strategies to reduce the risk of failure), prioritization (i.e., focusing resources in areas more likely to yield success), and effectively allocating limited resources. Ideally, web-based decision-support tools could have source code housed in accessible, open-access, public repositories with clear documentation and instructions to streamline their use and provide opportunities for tool comparison and improvement to meet evolving applications. When collaboratively developed and used by researchers and managers, decision-support tools can provide opportunities for coordinated and useful data generation, methods validation and augmentation, and more focused and applicable research.

Conclusions

Halfway through the international Decade on Ecosystem Restoration, the U.S. and other nations have made substantial progress that reveals key lessons for future restoration and research efforts. However, there are uncertainties and knowledge gaps that could improve the efficiency and effectiveness of seed-based restoration. Research and adjacent activities coordinated through the BLM Ecoregional Programs illuminate areas of native seed development and use that can be incorporated into future research and management frameworks. Moreover, lessons learned from these persistent programs can inform efforts at regional and local scales, or during the establishment of new national or international programs. Inevitably, a shared vision, sustained collaboration, and translation of research into user-friendly decision support tools can facilitate the continued relevance of native seed to land management efforts.

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