RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration

REVIEW ARTICLE

Practitioner tools for addressing knowing–doing gaps in seed-based restoration

Kristina E. Young[1,2], Tara B. B. Bishop[3], Danielle B. Johnson[4], Kevin Gunnell[5], Akasha Faist[6], Magda Garbowski[7], Olga Kildisheva[8], Danielle Neumann[4], Elise Gornish[9]

The increasing impact of global change drivers, including climate change, wildfires, and invasive plant species, is significantly transforming native plant communities in the western United States, prompting a strong focus on ecological restoration. One prominent restoration strategy involves using native seeds. However, achieving successful seed-based restoration faces several ecological and logistical challenges. Ecological obstacles can include seed predation, unsuccessful germination, and early seedling mortality, while logistical issues can involve ensuring the availability and suitability of seeds for specific sites. To address these challenges, a range of tools, including species selection tools, climate-adapted seed tools, seed handling resources, trait databases, and restoration information portals, have been developed to assist practitioners. Despite these resources, a significant gap exists between the research produced by scientists and its application by practitioners. Bridging this "knowing–doing" gap requires making information more available, relevant, current, and understandable for end users. Our goal is to highlight online tools that can address the knowing–doing gap in seed-based restoration to provide a resource for individuals who are interested in: (1) learning about available tools and (2) creating tools for practitioners. Efforts to improve tool usability, provide training, and encourage knowledge exchange are essential to enhancing restoration outcomes and effectively using native seeds to mitigate the effects of global change.

Key words: climate-informed seed selection, ecological bottlenecks in restoration, knowing–doing gap solutions, native plant material development, practitioner-relevant restoration tools

Implications for Practice

- Enhance practitioner usability: Develop and maintain online, seed-based restoration portals and tools that are usable and provide relevant, understandable information for practitioners.
- Bridge the knowing–doing gap: Implement strategies to integrate scientific research with practical application. This includes co-production of knowledge with practitioners, considering their needs, and incorporating their feedback.
- Streamline seed selection and logistics: Create tools that simplify the process of selecting and handling native seeds, considering regional and climate-specific factors. Tools should offer clear, actionable insights to facilitate effective restoration efforts.
- Invest in practitioner training: Provide efficient training programs for practitioners to ensure effective utilization of available tools and resources. This includes workshops, webinars, and instructional materials that align with their workflows and time constraints.

Introduction

The acceleration of global change drivers, such as climate change, catastrophic wildfires, and non-native plant invasion, is dramatically altering native plant communities in the western United States (Friedman et al. 2005; Davies et al. 2011; Havrilla et al. 2023). Many of these drivers reduce biodiversity, change fire regimes, and increase soil erosion (Svejcar et al. 2017; Duniway et al. 2019). The negative outcomes for human and natural communities have resulted in substantial interest and investment in ecological restoration; specifically, the deployment of native seeds as a restoration strategy (Barga et al. 2020). Current seed-based restoration efforts are being carried out by a variety of users, from private landowners to federal agencies, collectively managing 640 million acres of land in the United States (National Academies of Sciences, Engineering, and Medicine 2020). Broad U.S.-based policies, such as the 2021 Infrastructure Investment and Jobs Act (IIJA; P.L:117-58) and the 2022 Inflation Reduction

Author contributions: KEY wrote the first draft of the manuscript; TBBB, DBJ, KG, AF, MG, OK, DN, EG contributed to the ideas, tool identification, and writing of the manuscript.

[1]USDA-ARS Jornada Experimental Range, Las Cruces, NM, U.S.A.
[2]Address correspondence to K. E. Young, email kristina.young@usu.edu
[3]Department of Earth Science, Utah Valley University, Orem, UT, U.S.A.
[4]Colorado Parks and Wildlife, Grand Junction, CO, U.S.A.
[5]Utah Division of Wildlife Resources, Ephraim, UT, U.S.A.
[6]W.A. Franke College of Forestry and Conservation, University of Montana, Missoula, MT, U.S.A.
[7]Department of Animal and Range Sciences, New Mexico State University, Las Cruces, NM, U.S.A.
[8]The Nature Conservancy, Bend, OR, U.S.A.
[9]School of Natural Resources and the Environment, University of Arizona, Tucson, AZ, U.S.A.

doi: 10.1111/rec.70043
Supporting information at:
http://onlinelibrary.wiley.com/doi/10.1111/rec.70043/suppinfo

Act (IRA; P.L:117-169), directed billions of dollars into restoration efforts in the United States, including seeding and planting. These initiatives and funding suggest that seeding with native plants will continue to be a widely implemented approach for mitigating the impacts of global change and reducing biodiversity loss in the western United States.

Substantial resources have been, and continue to be, devoted to addressing the challenging task of achieving successful seed germination and plant establishment in semiarid to arid western U.S. climates (Svejcar et al. 2017). Ecological bottlenecks to seedling establishment have been explored extensively in the literature, including seed loss from movement off-site, predation, disease, unsuccessful germination, and post-germination/pre-emergent mortality (e.g. Kildisheva et al. 2018; Hardegree et al. 2020). Numerous logistical bottlenecks can also influence the availability of adequate quantities of seeds suitable for a restoration site, including time lags from production to harvest, volatility in the seed market, and cumbersome seed certification processes (McCormick et al. 2021; NASEM 2023). Many of these constraints are being addressed through a variety of efforts, including organized native plant material development processes (McCormick et al. 2021), developments in seed transfer zones for native species (Bower et al. 2014), and federal programs such as Bureau of Land Management Seeds of Success (Barga et al. 2020). These extensive and laudable efforts represent important components to accomplishing successful native plant restoration (Baughman et al. 2022).

The substantial resources, research, and attention devoted to native plant materials in the western United States present both a need and an opportunity to ensure that the resulting information is *usable*, *relevant*, and *easily understandable* for land managers, restoration practitioners, and property owners. However, a persistent challenge lies in bridging the gap between the information generated by scientists and its adoption by practitioners—commonly referred to as the "knowing–doing gap" (Esler et al. 2010; Matzek et al. 2014). This gap poses a major barrier to achieving restoration goals. Surveys indicate that while stakeholders are eager for solutions to persistent land management challenges, they often lack access to the critical information needed to address them (Li & Gornish 2020; Schohr et al. 2020). Knowing–doing gaps often arise when the needs of end users are not adequately considered and when practitioners' tacit knowledge is overlooked in research efforts (Hulme 2014). For instance, practitioners and land managers often face heavy workloads and limited time to process scientific findings, which can limit the integration of scientific findings into restoration action. Intentional efforts to bridge this gap, such as effective information sharing through tool development and online platforms, can help alleviate these logistical hurdles by making scientific results more available and actionable. Furthermore, fostering dialog between researchers and practitioners can lead to more targeted research, the development of practical tools, and ultimately, improved restoration outcomes (e.g. Bestelmeyer et al. 2021).

At the 2024 annual meeting of the Society for Range Management, we convened a group of restoration practitioners, seed producers, Cooperative Extension professionals, and restoration researchers to identify information-sharing strategies that can help fill knowing–doing gaps in native plant restoration in the western United States. Specifically, we discussed the utility and need for seed-based tools and information portals that provide *readily usable*, *relevant*, and *easily understandable* information for end users. Leveraging the collective expertise of our convened group, we compiled a list of online tools and information platforms ("tools" hereafter) that group members identified as broadly useful to restoration practitioners in the western United States, freely accessible, and easily found online. While we did not conduct an exhaustive search for all available tools, the tools discussed below represent a large sample of those currently available in the restoration field. We provide a brief overview of these practitioner-available tools that help fill knowing-doing gaps in the realm of seed-based restoration in western U.S. landscapes and discuss some common limitations and recommendations. We sorted tools into five main categories: (1) *Native Plant Species Selection Tools*, (2) *Climate-Informed Seed Selection Tools*, (3) *Seed Costs/Seed Handling Tools*, (4) *Seed/Plant Trait Information Databases*, and (5) *Portals for Restoration Implementation Information* (Table 1). We conclude that the increasing availability of practitioner-relevant restoration tools is helping to narrow the knowing–doing gap in seed-based restoration (Fig. 1). However, we note that these tools often fail to fully integrate practitioner knowledge, preferred methods of use (i.e. how and when practitioners wish to use the tools), and vary in their usability (Table S1; Fig. 1).

Practitioner-Available Tools that Help Fill Knowing—Doing Gaps in Seed-Based Restoration

Native Plant Species Selection Tools

Selecting the right species and seed sources and knowing where to obtain them can be a challenge for practitioners who need to (1) quickly and easily build native plant species lists for themselves or others in a restoration setting, and (2) access information about seed availability in the time frames needed for decision-making. Specifically, accessing information about appropriate seed mixes in a given location, regional seed producers, seed costs, and seed availability can be barriers to restoration implementation and success (McCormick et al. 2021).

Various practitioner-oriented online seed selection tools are readily available, offering information on suitable native species for restoration projects in the western United States. (Table 1). These tools serve as starting points for planning and implementation and can be general or tailored to specific management goals (Table 1). Tailored tools includethe Ecoregional Revegetation Application (ERA) Tool, which aids in selecting native plants for roadside revegetation and pollinator habitat enhancement, categorized by U.S. Environmental Protection Agency (EPA) Level III Ecoregions; the TransPlant seed tool, which assists landscape architects in choosing regionally appropriate plant species based on factors like elevation, rainfall, soil type, and regional plant communities in California; and the Phase Seed Selection tool, which offers seed mix recommendations tailored for site planners and vegetation managers working on solar energy projects.

Table 1. List of seed-based restoration tools available to practitioners and researchers working in the western United States.

Category	*Tool*	*Description*	*Website*	*Citation*	*Additional citations*
Native Plant Species Selection Tools	Colorado Seed Tool	An interface that allows users to enter project management goals (ex. elk habitat, greater sage-grouse habitat, fire reclamation, etc.) and site conditions to either produce a seed menu of candidate species for a seed mix or to verify if an existing seed mix will meet management goals and establish well at a site.	https://cpw.widencollective.com/assets/share/asset/z6owwh8sfa	Colorado Parks and Wildlife (2023)	
	Ecoregional Revegetation Application Tool	A map-based, searchable application to select native plants for restoration and pollinator habitat enhancement by U.S. Environmental Protection Agency (EPA) Level III Ecoregions.	https://www.nativerevegetation.org/era/	United States Department of Agriculture and US Federal Highway Administration (2017)	
	EcoRestore Arizona—Native Plant Species Finder Tool (AZ, U.S.A.)	A platform to provide an assessment with which to investigate potential species based on site characteristics and management goals in Arizona.	https://ecorestore.arizona.edu/	University of Arizona (n.d.)	
	EcoRestore Nevada—Native Plant Species Finder Tool (NV, U.S.A.)	A platform to provide an assessment with which to investigate potential species based on site characteristics and management goals in Nevada.	https://ecorestorenv.arizona.edu/	EcoRestore Nevada (n.d.)	
	EcoRestore Utah—Native Plant Species Finder Tool (UY, U.S.A.)	A platform to provide an assessment with which to investigate potential species based on site characteristics and management goals in Utah.	https://extension.usu.edu/ecorestore/	Utah State University (n.d.)	
	Movaje Seed Menus	A spatial decision-support tool designed to help land managers create suitable seed mixes for restoration sites, such as a burned area or other mapped spatial feature. The application provides coverage for the Mojave Desert ecoregion.	https://www.usgs.gov/software/mojave-seed-menus-a-new-spatial-tool-restoration-software-release-v10	Shryock et al. (n.d.)	Shryocet al. (2022)
	Native Seed Selection Tool (TX, U.S.A.)	A tool to create a custom seed mix list of recommended varieties with % of planting rate and a Pure Live Seed rate. Also included are licensed seed vendors along with contact information for local technical guidance.	https://www.ckwri.tamuk.edu/research-programs/texas-native-seeds-program-tns/native-seed-selection-tool	Texas A&M University-Kingsville (n.d.)	
	Phase Seed Selection Tool	Provides seed mixes for site planners and vegetation managers of solar energy project sites that meet site objectives	https://phase.erc.uic.edu/SeedSelection	U.S. Department of Energy (n.d.)	
	Seed-Spec Selection Tool (southwest/southern United States)	A geo-spatially enabled web application to develop custom native seed blends for re-vegetation projects using site specific soil and plant information and minimal user inputs.	https://seedspec.com/	Seed-Spec (n.d.)	
	TransPlant Seed Plant Calculator (CA, U.S.A.)	A seed plant calculator tool to aid Caltrans Landscape Architects when selecting regionally appropriate	https://dot.ca.gov/programs/design/lap-	State of California (n.d.)	

Table 1. Continued

Category	*Tool*	*Description*	*Website*	*Citation*	*Additional citations*
		plant species for erosion control, revegetation, biofiltration, and other highway planting situations.	seed-plant-calculator-transplant		
	Wildflower Farm Seed Selector Tool	Suggests seeds for property owners based on site specific growing conditions and/or by state or province.	https://www.wildflowerfarm.com/seed-selector.html?Per_Page=60&Sort_By=name_asc&prod_state_province=Colorado	Goldberger and Jenkins (n.d.)	
Climate-Informed Seed Selection Tool	The Climate-Adapted Seed Tool (CAST)	A tool to help land managers identify seed sources best adapted to local climate conditions at their planting sites. CAST currently serves five western U.S. states (CA, OR, WA, ID, and NV), though some features are limited to California.	https://reforestationtools.org/climate-adapted-seed-tool/	Stewart et al. (n.d.)	
	The Climate Smart Seedlot Selection Tool (SST)	A GIS mapping program to help forest managers match seedlots with planting sites based on climatic information. The climates of the planting sites can be chosen to represent current climates, or future climates based on selected climate change scenarios.	https://seedlotselectiontool.org/sst/	Howe et al. (n.d.-a)	St. Clair et al. (2022)
	Climate Smart Restoration Tool (CSRT)	A tool to provide information on seed collection and transfer of native plants. Maps current and future seed transfer limits for plant species with or without genetic information using climate data generating from ClimateNA.	https://climaterestorationtool.org/csrt/	Howe et al. (n.d.-a)	St. Clair et al. (2022)
	Climate Distance Mapper	A spatial decision-support tool to help land managers match seed sources with restoration sites, which allows users to rank the suitability of seed sources for restoration sites by displaying the multivariate climate distance from user-specified input points to the surrounding landscape. Users can perform calculations for either the current or future climates.	https://usgs-werc-shinytools.shinyapps.io/Climate_Distance_Mapper/	Shryocket al. (2022)	
	Native Plant Seed Mapping Toolkit (Seed Selection Tool and Climate Partitioning Tool)	Tools to visualize the climatic similarity between a restoration material's (RM's) location of origin and a defined geographic area. This tool helps users (1) prioritize which RMs may be best matched to a restoration site and (2) identify locations where RMs need to be developed. Further climate partitioning allows users to split climate variation into a selected number of groups, or partitions, across a defined geographic area.	https://www.usgs.gov/apps/seed-toolkit/	Doherty and Andrews (n.d.)	Doherty et al. (2017)
	Species Potential Habitat Tool (SPHT)	Tool offering forest managers insights into suitable dominant tree species types for specific sites across different climate change scenarios and can be used with the Seedlot Selection Tool to allow users to	https://specieshabitattool.org/spht/	Howe et al. (n.d.-b)	

Table 1. Continued

Category	*Tool*	*Description*	*Website*	*Citation*	*Additional citations*
		explore options for both species-level and within-species assisted migration.			
Seed Costs/Seed Handling Tools	Phase Cost Comparison Tool	An online platform to compare cost analysis of different vegetation configurations on utility-scale solar facilities.	https://phase.erc.uic.edu/CostComparison	University of Illinois Chicago and Stantec (n.d.)	
	Seed Selection Cost Comparison Decision Tool	A tool to consider yield and economic returns of selecting seed products. Utilizing test plot or in-field yield results, producers can determine which seed hybrids or varieties provide the best opportunity to maximize production and profitability.	https://www.canr.msu.edu/resources/seed-selection-cost-comparison-decision-tool	LaPorte (2022)	
	Seed Information Database	A compilation of seed biological trait data, with records derived from measurements and observations on seed collections held in Royal Botanic Garden Kew's Millennium Seed Bank and from other unpublished and published sources providing user-friendly access to information on seed weight, storage behavior, germination requirements, and other traits for more than 50.000 plant taxa.	https://ser-sid.org/about	Society for Ecological Restoration, International Network for Seed Based Restoration and Royal Botanic Gardens Kew (2023)	Liu et al. (2019)
Seed/Plant Trait Information/ Databases	TRY Plant Trait Database	A comprehensive web-archive of the functional biodiversity of plants at the global scale by assembling, harmonizing, and distributing published and unpublished data on functional plant traits complemented by a wide range of metadata—methodological and environmental information.	https://try-db.org/TryWeb/Home.php	Boenisch and Kattge (n.d.)	Kattge et al. (2020)
	R Packages: Select	Produces trait-based models that can be used to generate ranges of species abundances to test theories about which traits, which trait values and which species assemblages are most effective for achieving functional outcomes.	https://cran.r-project.org/web/packages/Select/index.html	Laughlin and (2018)	
	R Packages: RPSS Platform	Software to assist users in selecting plant species for particular purposes (e.g. restore the degraded ecosystems and others). It is written in R language and integrated with external R packages, including the packages that computing similarity indexes, providing graphic outputs, and offering web functions. The software has a web-based graphical user interface that allows users to execute required functions via checkboxes and buttons.	https://www.frontiersin.org/journals/ecology-and-evolution/articles/10.3389/fevo.2021.570454/full	Wang et al. (2021)	
	Restoring Ecosystem Services Tool (REST)	A program to help users select a suite of plant species whose life history traits relate to addressing a specific management objective. Trait data from global databases have been incorporated into the program, providing some data from many species.	https://www.fs.usda.gov/research/treesearch/58004	Rayome et al. (2019)	

Table 1. Continued

Category	Tool	Description	Website	Citation	Additional citations
		Users define management objectives from a menu of available restoration goals (drought tolerance, fire tolerance, successional facilitation, or carbon storage) to filter for connected functional traits.			
Portals for Restoration Implementation Information	EcoRestore Portal	A collection of websites that are committed to bringing you the best, most useful and most up-to-date resources to get ecological restoration done. Can be used for creating a restoration plan, choosing, procuring and deploying plant materials, maintaining a site and more. EcoRestore is also a community where gardeners, managers, native plant lovers and land managers can share knowledge.	https://ecorestoreportal.com/	University of Arizona (n.d.)	
	Revegetation Equipment Catalog	A catalog providing descriptions, applications, photos, and vendors of equipment used for seed collection and cleaning, site preparation, revegetation, and vegetation management.	https://revegetation.greatbasinfirescience.org/	Gucker (n.d.)	
	Society for Ecological Restoration (SER) Standards Tools	A page providing the most up to date, downloadable versions of key tools within the suite of SER ecological restoration standards.	https://www.ser.org/page/Standards-Tools	Society for Ecological Restoration (n.d.)	
	Western Forbs: Biology, Ecology, and Use in Restoration	An online book and lookup table synthesizing all existing research and practical experience gained over the last 20 years. It is designed to aid seed collectors, seed growers, nurserymen, landowners, restoration practitioners, and land managers as they increase the supply and use of native forbs. Each chapter features an individual species' biology, ecology, seed technology, and use in restoration based on literature and data available at the time of publication.	https://westernforbs.org/	Gucker and Shaw (2019)	

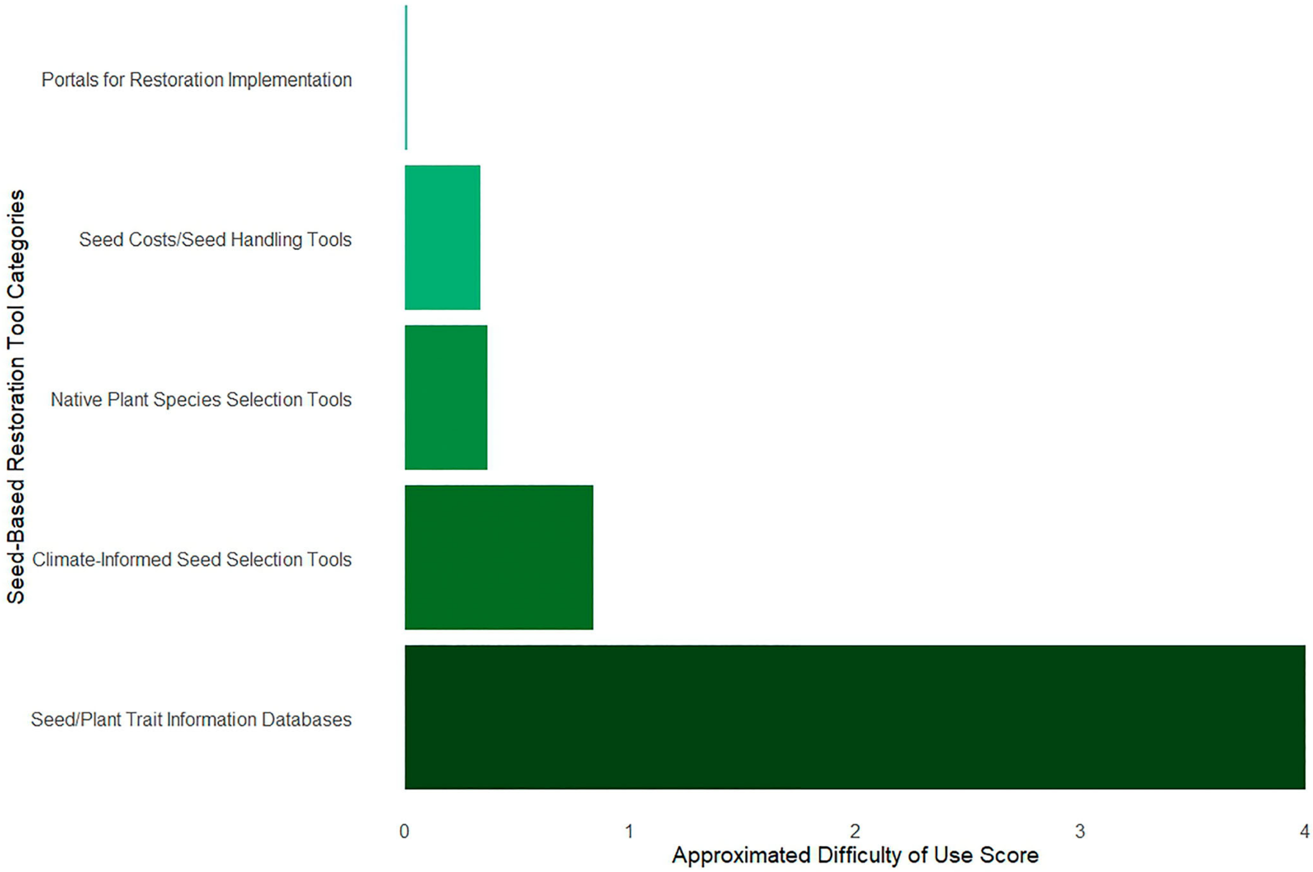

Figure 1. The usability of seed-based restoration tools to practitioners in the western United States was variable. Using criteria related to practitioner usability (detailed in Table S1), manuscript authors scored the tools listed in Table 1. Lower scores indicate tools that are more usable for practitioners, while higher scores indicate tools that are less usable for practitioners. Although these averages do not reflect every tool in a given category, they underscore the need for more resources to support practitioners in climate-informed seed selection and trait-based seed and plant restoration efforts.

Other tools use geospatial data or defined geographic areas to generate more targeted seed lists for reclamation projects (Table 1). For example, the Seed-Spec Selection Tool provides suggested native seed blends for revegetation based on soil and ecological information, primarily in the South-Central United States. Additionally, the Mojave Seed Menu use habitat suitability models and key species traits to generate customized seed mixes for locations within the Mojave Desert ecoregion. Other tools have been organized around county locations, such as the EcoRestore Native Plant Species Finder, the Colorado Seed Tool, the Wildflower Farm Seed Collector Tool, and the Texas Native Seed Selection Tool, which offer native plant species lists and seed mix recommendations based on user-provided site information (Table 1).

Many of these tools provide research-based information in understandable formats that managers can freely access, providing recommendations for seed/species selections that are readily available to a range of end-users. Some tools are more transparent than others in referencing information sources, largely based on who created the tool and who the tool is intended for (e.g. tools created by nurseries do not cite sources as frequently as tools created by academics). Additionally, the information informing the seed list varies between tools, with some providing more site-specific information than others. For example, the EcoRestore Native Plant Species Finder database primarily uses information from US Department of Agriculture Plants and peer-reviewed literature, while the Colorado Seed Tool also incorporates information provided by practitioners into the database. An important improvement for making these tools more relevant to practitioners would be to incorporate opportunities for managers to provide feedback. This could facilitate knowledge sharing and help address the context-specific outcomes of species selection through localized comments and suggestions. For example, the Colorado Seed Tool includes an online forum, organized by county, where practitioners can share and compare their local knowledge, enhancing the tool's usefulness and community engagement.

Climate-Informed Seed Selection Tools

Restoration efforts are more likely to succeed in the long term when they account for future climate conditions at the restoration site (Butterfield et al. 2017). Predicting how climate change will impact species' performance is crucial for selecting appropriate seed sources and optimizing restoration success. Several tools have been developed to assist with this process by providing insights into seed performance across various climates, considering both current conditions and future projections.

For tree species, the Climate-Adapted Seed Tool estimates potential declines in productivity based on seed source suitability to the local climate (Table 1). Similarly, the Climate Smart Seedlot Selection Tool matches tree seedlings, or seedlots, with suitable planting sites based on climate variables such as temperature and precipitation, considering both current conditions and projected climate scenarios. To predict future species distributions, the Species Potential Habitat Tool guides forest managers in selecting suitable dominant tree species across various climate change scenarios. When used alongside the Seedlot Selection Tool, it enables exploration of both species-level and within-species assisted migration strategies (Table 1).

For non-tree species, tools such as the Climate Smart Restoration Tool offer seed collection and transfer guidelines by using current and future seed transfer limits for plant species with or without genetic information generated from monthly climate data (Table 1). The Native Plant Seed Mapping Toolkit provides maps that identify locations where seed from a particular source is likely to be well adapted, based on climate similarity between the seed source and planting site. Additionally, the Climate Distance Mapper Tool evaluates the suitability of a seed source for a restoration site based on current or projected climate conditions, including components of precipitation and temperature.

Together, these tools offer valuable insights for developing restoration strategies that account for both current and projected climate conditions. However, limitations remain in terms of resource availability and the implementation of provenance trials. One key challenge is the learning curve associated with using these tools, which can be time-consuming for practitioners who are often constrained by limited resources (Meredith et al. 2021; Fig. 1). Ensuring tools related to climate change are honed and created with end-users and directly relevant to practitioner workflows can help to overcome some of these limitations (Beier et al. 2017). Further, expanding provenance testing efforts to cover more species, specifically forbs and graminoid species, which are commonly used for restoration (Gucker & Shaw 2019) is needed. Forbs and graminoid species have fewer empirical provenance trials to inform seed sourcing compared to trees (Vitt et al. 2022); therefore, expanded provenance testing could help address remaining knowledge gaps. Ultimately, combining models that recommend species based on site characteristics and location information with climate projections and genetic data could become the gold standard for seed sourcing/transfer guidance. The need for this gold standard was highlighted by findings that suggest the likelihood of mixing genetically different plant individuals increases with distance in parts of the western United States, from about 8% at 50 km to nearly 80% at 500 km regardless of their climate-informed seed transfer zone (Massatti et al. 2020).

Seed Costs/Seed Handling Tools

Informed seed purchasing and handling logistics are essential for successful restoration projects, as practitioners must make crucial decisions regarding seed costs, viability, storage, cleaning, purity, and dormancy management. These decisions directly impact the success of restoration outcomes, as seed quality and preparation play a pivotal role in establishing healthy plant populations. While some seed information is available from producers (e.g. on seed bags), the absence of centralized guidance often presents logistical challenges for practitioners, particularly when dealing with varying seed types, species requirements, and local environmental conditions (e.g. Gebeyehu 2020). When local knowledge is unavailable, practitioners must rely on generalized knowledge or trial and error, both of which can lead to inefficiencies and increased costs.

A limited number of tools have been developed to assist with seed purchasing and handling logistics (Table 1). For example, the Seed Selection Cost Comparison Decision Tool helps producers assess the economic returns on seed products, which is an important consideration for practitioners (Brodt et al. 2008). When restoration efforts are integrated with large-scale energy projects, tools like the Phase Cost Comparison Tool enable site owners and developers to evaluate the economic costs and benefits of incorporating pollinator plantings at large-scale solar facilities. These tools offer a starting point for practitioners to plan restoration projects and estimate costs. However, given the high likelihood that many seeds will not establish across variable conditions that may be unfavorable for survival (Shackelford et al. 2021), tools that calculate and include some measure of the probability of a restoration treatment being successful on a per-unit-area basis—such as by dividing the cost of the treatment by the probability of success—could help practitioners estimate more realistic costs for achieving successful restoration. For example, in the Great Basin, when the probability of success was factored into the cost calculations, spatial variability in vegetation composition and soil factors that affected restoration outcomes led to orders of magnitude increases in restoration costs across a 1.5 km transect (Boyd & Davies 2012). To effectively plan seeding actions while considering spatial heterogeneity, tools like the Land Treatment Exploration Tool offer information on site characteristics (e.g. elevation, precipitation, and temperature), past treatments, and drought forecasts (Pilliod et al. 2018). These tools provide insights that can help identify optimal treatment locations and select the most effective methods to enhance the likelihood of achieving desired outcomes, similar to land potential classification approaches described in UNEP (2016). Ongoing refinement and broader application of such tools could significantly improve restoration success, especially as global change amplifies climatic and landscape variability.

To help guide informed seed handling, the Seed Information Database, managed by the Society for Ecological Restoration's International Network for Seed-based Restoration, offers comprehensive information on storage behavior, seed weights, dispersal, and germination for over 50,000 seed plant taxa (Table 1). These data are a helpful and important starting point to guide seed handling strategies. However, the data are often derived from laboratory conditions, which do not necessarily replicate ecological behavior in the field (Forero et al. 2019). Furthermore, data is often provided in an unsynthesized format, with results from each experiment presented individually. While that format is helpful for scientists who need to understand nuances that might drive variability from one experiment to another, synthesizing the results to a mean or range of values can be an obstacle for practitioners. Moreover, ensuring that such databases incorporate practitioner and local knowledge is essential for bridging the knowing–doing gap (Hulme 2014), but this can be difficult to achieve in practice, as providing data may be a low priority for busy practitioners.

Other easily accessed avenues for obtaining seed handling information, such as manuals, printed books, and community events, can assist practitioners in determining storage requirements, cleaning techniques, and testing protocols while contributing to public outreach and education on best practices. For instance, conducting seed handling experiments as public outreach events where local community members collect the seeds that will be tested for viability (see the "Go Nuts!" program described in Cobb et al. 2020) can provide a means to gather information, reduce seed deterioration, and foster community engagement in restoration efforts (Adetumbi et al. 2010). Blending the information gathered by practitioners and communities with online tools is a challenging but worthwhile pursuit for restoration researchers to undertake.

Seed/Plant Trait Information Databases

Effectively utilizing seed-based restoration methods to achieve management objectives often requires careful consideration of plant and seed traits that align with these goals (Pywell et al. 2003; Funk et al. 2008). A comprehensive knowledge of plant traits can play a crucial role in restoration, serving as indicators of habitat tolerance, demographic outcomes, and ecosystem service contributions. Despite the availability of plant trait data relevant to restoration in peer-reviewed literature (e.g. Erickson et al. 2016; Guzzomi et al. 2016; Larson et al. 2023), applying these data to restoration can be challenging for several reasons (Funk et al. 2024). First is access to data. Even though many studies focus on using traits in restoration contexts, data associated with the studies is often not available (Ladouceur et al. 2022). Paywalls also prevent access to important trait-based findings. Second, the application of trait-based approaches to restoration often requires subject matter expertise. Global databases like the TRY plant trait database provide largely open-access information on myriad plant traits (Table 1). However, this and other plant trait databases only provide raw trait data (e.g. specific leaf area and leaf dry matter content) and they do not provide information on specific strategies or performance metrics that are important to restoration (e.g. drought tolerance, productivity). These and other performance metrics, such as seedling vigor, are often known and used by practitioners but are not often included in restoration research and knowledge dissemination platforms (Gornish et al. 2023). Because no databases link plant traits to plant performance in restoration settings, they remain primarily useful to researchers. Software, such as specialized analysis "packages" in R (e.g. restoptr, Select, RPSS Platform—which also has a software platform) and .exe files such as Restoring Ecosystem Services Tool, are helping to integrate trait-based approaches into research (Table 1). However, many of these tools remain inaccessible to most practitioners for the reasons described above and the added barrier of needing familiarity with a programming language. Subject matter expertise and more effective science translation are needed to link specific plant traits to plant performance and make this information easily accessible to land managers and restoration practitioners. Using equitable co-production to integrate practitioner knowledge, traditional ecological knowledge, and local knowledge alongside continued experimentation to link plant and seed trait databases with on-the-ground plant performance can bridge existing gaps and enhance the effectiveness of seed-based restoration efforts (Uprety et al. 2012).

Portals for Restoration Implementation Information

Effectively implementing seed delivery methods and ensuring successful germination is crucial for the success of restoration efforts (Erickson & Halford 2020). Guidance on seed sowing often highlights key factors such as selecting appropriate seeding equipment, tailoring strategies to specific species and site conditions, ensuring proper seed-to-soil contact, and overcoming barriers to germination and establishment (Kildisheva et al. 2018; Shaw et al. 2020; Johnson et al. 2023). Although general knowledge on effective application methods exists across diverse environments (e.g. Walker et al. 2004; Krautzer et al. 2012; Hardegree et al. 2016), site-specific recommendations are still limited, and much of this valuable information is effectively unavailable to practitioners who lack the time to engage with peer-reviewed literature.

To address these gaps, various online portals and centralized repositories have been developed to provide resources for practitioners (Table 1). These platforms compile state- or region-specific restoration information, offering practical guidance for users at all levels. For example, the EcoRestore Portals currently available in Utah, Arizona, and Nevada provide resources for designing, implementing, and monitoring restoration projects with information relevant to each state. Similarly, the Revegetation Equipment Catalog focuses on the Great Basin and provides detailed descriptions, applications, photos, and vendor information for equipment used in seed collection, cleaning, site preparation, revegetation, and vegetation management. The online book and lookup table, Western Forbs: Biology, Ecology, and Use in Restoration, offers a comprehensive species lookup table with information on the biology, ecology, seed technology, and restoration use of western forbs, based on existing literature and data. This resource is especially valuable, as forbs are ecologically important but often underutilized functional groups in seeding efforts (Nerlekar et al. 2024). Globally relevant platforms, such as the Society for Ecological Restoration website, further support restoration efforts by offering tools like the Ecological Recovery Wheel and the Standards for Native Seeds in Ecological Restoration, now available in multiple languages to improve access across diverse regions. Together, these resources contribute to making restoration knowledge more available and actionable for practitioners.

Despite these advancements, many resources remain fragmented or underutilized. Expanding centralized platforms to incorporate recent research findings, practitioner feedback, and locally relevant case studies could enhance their effectiveness. For instance, including user-generated insights and real-world experiences—similar to practitioner forums linked to seed selection tools—could create dynamic, interactive repositories. Furthermore, we strongly encourage restoration researchers to prioritize translating their findings into easily understandable formats and ensuring their resources are included in these types of platforms.

Limitations of Practitioner Tools and Suggestions for Bridging the Knowing–Doing Gap

All tools have inherent limitations. Information provided in online tools is often coarse; for example, seed lists from seed menu tools might be too broad to be useful, depending on the scope of the restoration goal. Additionally, plant species tools may recommend and provide information on species that may not be available to purchase due to supply chain limitations or that may be financially unviable for practitioners (Ladouceur et al. 2018; León-Lobos et al. 2020). Compiling and storing information in databases can be risky due to the possibility of information becoming obsolete or unavailable due to personnel changes or the end of funding that supported the hosting and maintenance of the tool. Further, databases that primarily use greenhouse or laboratory trials have limited utility when applied to decision-making in field settings (Forero et al. 2019). For tools to be adopted by practitioners, tool creators must create tools that meet practitioner needs and must ensure practitioners are informed about available tools and trained in how to use them (Meredith et al. 2021; Bestelmeyer et al. 2024). Many authors on this paper have anecdotally heard practitioners complain of "tool fatigue" where tools are introduced but are not directly relevant to practitioner needs, are considered suspect in their trustworthiness, or require too much learning time. Creating additional tools can be stymied by a lack of incentive or reward for creating tools for those in research positions, and other institutional barriers such as limitations around coproduction (Pearman & Cravens 2022). Despite these limitations, creating tools and compiling information are still considered valuable by practitioners (Li & Gornish 2020; Schohr et al. 2020) and represent a solvable bottleneck in the restoration pipeline.

Available tools vary in their usability for practitioners (Fig. 1). Many of the tools described here contain a wealth of information and detail. While capturing this detail is critical, too much detail and complexity (e.g. the amount of input information required to receive results in a selection tool) can be a detriment to busy practitioners who are under time pressure to procure and plant seed. On the other hand, tools that provide broad information such as some of the seed selection tools and restoration information portals may gloss over nuances and interactions that can be important to restoration outcomes. For optimum efficiency, the best level of detail is the minimum level of detail needed to produce desirable results. Because the important details will vary from region to region and project to project, providing the best level of detail can be challenging and often unknown. Consequently, bridging the knowing–doing gap might require more than one step. Tools capturing complexity and nuance, such as those typically produced by researchers, can be utilized in the creation of synthetic tools more easily available to practitioners. For example, the Native Plant Seed Mapping Toolkit requires users to input the source population's coordinates, set climate similarity thresholds, and prioritize climate metrics for each plant material. While practitioners can certainly handle this complexity, they often lack the time to dedicate such detailed attention to a single plant material for one project. To address this, the Colorado Seed Tool simplifies the process by using the Toolkit's output to rank plant materials (e.g. cultivars or genetically unique sources) for each county in Colorado. Practitioners can enter their county and elevation to receive a list of genetically appropriate plant materials. However, this county-level synthesis may overlook important nuances, and appropriate options might not always be available or feasible. When input details are accessible and time permits, direct use of the Toolkit can be more effective. Balancing detail and usability is essential for bridging the knowing–doing gap. Determining the level of detail practitioners can effectively use—and evaluating whether it provides meaningful improvements over current practices—is crucial. This highlights the importance of co-production, where iterative use of tools by practitioners creates a feedback loop of information sharing and refinement, resulting in continuous improvement and better outcomes.

Summary and Recommendations

The gap between researchers and practitioners in seed-based restoration has narrowed in recent decades, as evidenced by the growing number of tools designed for practitioners. However, further progress is needed to fully bridge the knowing–doing gap. Closing this gap requires not only delivering experimentally tested data to end users but also fostering knowledge exchange that incorporates Indigenous and local knowledge systems. For instance, Diné kinship frameworks have been successfully used alongside Climate-Forest Vegetation Simulator models for forest management (Yazzie et al. 2019), demonstrating the potential for such collaborative approaches in restoration.

To improve tool development, utility, and usability, researchers can lead efforts such as: (1) Building trust with practitioners through respect for their time, knowledge, and expertise; (2) designing experiments and tools with end-users in mind; (3) co-producing tools and science in collaboration with practitioners; (4) offering practical training on tool application for specific "use cases;" (5) sharing findings at management-relevant meetings; (6) Encouraging the publication of synthesis papers in non-technical journals; and (7) actively seeking and incorporating practitioner feedback into tool updates (Gornish et al. 2021). By adopting these practices, researchers can enhance the accessibility and relevance of restoration tools, facilitate effective knowledge exchange, and ultimately contribute to greater success in seed-based restoration efforts.

Acknowledgments

Thank you to workshop participants at the Society for Range Management 2024 seeding workshop, the Institute for Applied

Ecology for compiling a list of restoration tools that we used as a starting place to find available restoration tool resources, and L. Brandt, M. Gordon, A. E. Montgomery, and R. L. Nelson, who helped with tool information compilation. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This work was funded by the Renewable Resources Extension Act – National Focus Fund Projects and the Western Integrated Plant Center, USDA National Institute of Food and Agriculture.

LITERATURE CITED

Adetumbi JA, Saka JO, Fato BF (2010) Seed handling system and its implications on seed quality in South Western Nigeria. Journal of Agricultural Extension and Rural Development 2:133–140

Barga SC, Olwell P, Edwards F, Prescott L, Leger EA (2020) Seeds of success: a conservation and restoration investment in the future of US lands. Conservation Science and Practice 2:e209. https://doi.org/10.1111/csp2.209

Baughman OW, Kulpa SM, Sheley RL (2022) Four paths toward realizing the full potential of using native plants during ecosystem restoration in the Intermountain West. Rangelands 44:218–226. https://doi.org/10.1016/j.rala.2022.01.003

Beier P, Hansen LJ, Helbrecht L, Behar D (2017) A how-to guide for coproduction of actionable science. Conservation Letters 10:288–296. https://doi.org/10.1111/conl.12300

Bestelmeyer BT, McCord SE, Browning DM, Burkett LM, Elias E, Estell RE, et al. (2024) Fulfilling the promise of digital tools to build rangeland resilience. Frontiers in Ecology and the Environment 22:e2736. https://doi.org/10.1002/fee.2736

Bestelmeyer BT, Spiegal S, Winkler R, James D, Levi M, Williamson J (2021) Assessing sustainability goals using big data: collaborative adaptive management in the Malpai borderlands. Rangeland Ecology & Management 77:17–29. https://doi.org/10.1016/j.rama.2021.03.002

Boenisch G, Kattge J (n.d.) Quantifying and scaling global plant trait diversity. TRY Plant Trait Database. https://try-db.org/TryWeb/Home.php

Bower AD, St. Clair JB, Erickson V (2014) Generalized provisional seed zones for native plants. Ecological Applications 24:913–919. https://doi.org/10.1890/13-0285.1

Boyd CS, Davies KW (2012) Spatial variability in cost and success of revegetation in a Wyoming big sagebrush community. Environmental Management 50:441–450. https://doi.org/10.1007/s00267-012-9894-6

Brodt S, Klonsky K, Jackson L, Brush SB, Smukler S (2008) Factors affecting adoption of hedgerows and other biodiversity-enhancing features on farms in California, U.S.A. Pages 195–206. In: Advances in agroforestry. Springer, Dordrecht, The Netherlands

Butterfield BJ, Copeland SM, Munson SM, Roybal CM, Wood TE (2017) Prestoration: using species in restoration that will persist now and into the future. Restoration Ecology 25:S155–S163. https://doi.org/10.1111/rec.12381

Cobb M, Woods MJ, McEwan RW (2020) Assessing seed handling processes to facilitate a community-engaged approach to regional forest restoration. Forests 11:474. https://doi.org/10.3390/f11040474

Colorado Parks and Wildlife (2023) Colorado Seed Tool (Version 1.3) (Mobile App). App Store. https://apps.apple.com/us/app/colorado-seed-tool/id6450682318 (accessed 4 Jun 2024)

Davies K, Boyd C, Beck J, Bates J, Svejcar T, Gregg M (2011) Saving the sagebrush sea: an ecosystem conservation plan for big sagebrush plant communities. Biological Conservation 144:2573–2584. https://doi.org/10.1016/j.biocon.2011.07.016

Doherty K, Andrews C (n.d.) Native Plant Seed Mapping Toolkit (seed selection tool & climate partitioning tool). USGS Science for a Changing World. https://www.usgs.gov/apps/seed-toolkit/ (accessed 4 Jun 2024)

Doherty KD, Butterfield BJ, Wood TE (2017) Matching seed to site by climate similarity: techniques to prioritize plant materials development and use in restoration. Ecological Applications 27:1010–1023. https://doi.org/10.1002/eap.1505

Duniway MC, Pfennigwerth AA, Fick SE, Nauman TW, Belnap J, Barger NN (2019) Wind erosion and dust from US drylands: a review of causes, consequences, and solutions in a changing world. Ecosphere 10:e02650. https://doi.org/10.1002/ecs2.2650

EcoRestore Nevada (n.d.) Native plant species finder tool (Nevada, U.S.A.). EcoRestore Portal Restore Nevada’s Native Plants. https://ecorestorenv.arizona.edu/ (accessed 4 Jun 2024)

Erickson TE, Barrett RL, Merritt DJ, Dixon KW (2016) Pilbara seed atlas and field guide: plant restoration in Australia’s arid northwest. CSIRO Publishing, Dickson, Australian Capital Territory, Australia

Erickson VJ, Halford A (2020) Seed planning, sourcing, and procurement. Restoration Ecology 28:S219–S227. https://doi.org/10.1111/rec.13199

Esler KJ, Prozesky H, Sharma GP, McGeoch M (2010) How wide is the “knowing-doing” gap in invasion biology? Biological Invasions 12:4065–4075. https://doi.org/10.1007/s10530-010-9812-x

Forero LE, Grenzer J, Heinze J, Schittko C, Kulmatiski A (2019) Greenhouse-and field-measured plant-soil feedbacks are not correlated. Frontiers in Environmental Science 7:184. https://doi.org/10.3389/fenvs.2019.00184

Friedman JM, Auble GT, Shafroth PB, Scott ML, Merigliano MF, Freehling MD, Griffin ER (2005) Dominance of non-native riparian trees in western U.S.A. Biological Invasions 7:747–751. https://doi.org/10.1007/s10530-004-5849-z

Funk JL, Cleland EE, Suding KN, Zavaleta ES (2008) Restoration through reassembly: plant traits and invasion resistance. Trends in Ecology & Evolution 23:695–703. https://doi.org/10.1016/j.tree.2008.07.013

Funk JL, Eviner VT, Garbowski M, Valliere JM (2024) Empirical tests of trait–function relationships are crucial for advancing trait-based restoration: a response to merchant et al. (2023). Restoration Ecology 32:e14254. https://doi.org/10.1111/rec.14254

Gebeyehu B (2020) Review on: effect of seed storage period and storage environment on seed quality. International Journal of Applied Agricultural Sciences 6:185–190. https://doi.org/10.11648/j.ijaas.20200606.14

Goldberger M, Jenkins P (n.d.) Wildflower farm seed selector tool. Wildflower Farm. https://www.wildflowerfarm.com/seed-selector.html (accessed 4 Jun 2024)

Gornish ES, Campbell C, Svejcar L, Munson SM, Vaughn K, Spaeth MK, Yelenik SG, Wolf A, Mitchell R (2023) Functional traits are used in restoration practice: a response to merchant et al. (2022). Restoration Ecology 31:e13880. https://doi.org/10.1111/rec.13880

Gornish ES, McCormick M, Begay M, Nsikani MM (2021) Sharing knowledge to improve ecological restoration outcomes. Restoration Ecology 32:e13417. https://doi.org/10.1111/rec.13417

Gucker CL (n.d.) Revegetation equipment catalog. Great Basin Fire Science Exchange, Reno, Nevada; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. https://revegetation.greatbasinfirescience.org/ (accessed 4 Jun 2024)

Gucker CL, Shaw NL (2019) Western forbs: biology, ecology, and use in restoration. Great Basin Fire Science Exchange, Reno, Nevada; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. http://greatbasinfirescience.org/western-forbsrestoration (accessed 4 Jun 2024)

Guzzomi AL, Erickson TE, Ling KY, Dixon KW, Merritt DJ (2016) Flash flaming effectively removes appendages and improves the seed coating potential of grass florets. Restoration Ecology 24:S98–S105. https://doi.org/10.1111/rec.12386

Hardegree SP, Jones TA, Roundy BA, Shaw NL, Monaco TA (2016) Assessment of range planting as a conservation practice. Rangeland Ecology & Management 60:237–247. http://dx.doi.org/10.1016/j.rama.2016.04.007

Hardegree SP, Sheley RL, James JJ, Reeves PA, Richards CM, Walters CT, Boyd CS, Moffet CA, Flerchinger GN (2020) Germination syndromes and their relevance to rangeland seeding strategies in the intermountain western United States. Rangeland Ecology & Management 73:334–341. https://doi.org/10.1016/j.rama.2019.11.004

Havrilla CA, Bradford JB, Yackulic CB, Munson SM (2023) Divergent climate impacts on C3 versus C4 grasses imply widespread 21st century shifts in grassland functional composition. Diversity and Distributions 29:379–394. https://doi.org/10.1111/ddi.13669

Herrick JE, Arnalds O, Bestelmeyer BT, Brignezu S, Han G, Johnson MV, Lu Y, Montanarella L, Pengue W, Toth G (2016) Unlocking the sustainable potential of land resources: Evaluation systems, strategies and tools. A report of the working group on land and soils of the International Resource Panel.

Howe G, Clair BS, Stevenson-Molnar N, Ward B, Bachelet D (n.d.-a) The Climate Smart Seedlot Selection Tool (SST). Seedlot Selection Tool. https://seedlotselectiontool.org/sst/ (accessed 4 Jun 2024)

Howe G, St.Clair B, Stevenson-Molnar N, Ferschweiler K, Klinkow B, Ward B (n.d.-b) Species Potential Habitat Tool (SPHT). https://specieshabitattool.org/spht/

Hulme PE (2014) Bridging the knowing–doing gap: know-who, know-what, know-why, know-how and know-when. Journal of Applied Ecology 51:1131–1136. https://doi.org/10.1111/1365-2664.12321

Johnson AJ, Geary B, Hulet A, Madsen MD (2023) Breaking dormancy and increasing restoration success of native penstemon species using gibberellic acid seed coatings and U-shaped furrows. Plants 12:4005. https://doi.org/10.3390/plants12234005

Kattge J, Bönisch G, Díaz S, Lavorel S, Prentice IC, Leadley P, et al. (2020) TRY plant trait database-enhanced coverage and open access. Global Change Biology 26:119–188. https://doi.org/10.1111/gcb.14904

Kildisheva OA, Erickson TE, Merritt DJ, Madsen MD, Dixon KW, Vargas J, Amarteifio R, Kramer AT (2018) Do abrasion-or temperature-based techniques more effectively relieve physical dormancy in seeds of cold desert perennials? Rangeland Ecology & Management 71:318–322. https://doi.org/10.1016/j.rama.2018.02.004

Krautzer B, Graiss W, Haslgrübler P, Golinski P (2012) Site assessment and preparation of receptor sites. Pages 39–42. In: Scotton M, Kirmer A, Krautzer B (eds) Practical handbook for seed harvest and ecological restoration of species-rich grasslands. Cooperativa Libraria Editrice, Università di Padova, Padova, Italy

Ladouceur E, Jiménez-Alfaro B, Marin M, De Vitis M, Abbandonato H, Iannetta PP, Bonomi C, Pritchard HW (2018) Native seed supply and the restoration species pool. Conservation Letters 11:e12381. https://doi.org/10.1111/conl.12381

Ladouceur E, Shackelford N, Bouazza K, Brudvig L, Bucharova A, Conradi T, et al. (2022) Knowledge sharing for shared success in the decade on ecosystem restoration. Ecological Solutions and Evidence 3:e12117. https://doi.org/10.1002/2688-8319.12117

LaPorte J (2022) Seed selection cost comparison decision tool. MSU Extension Farm Management, East Lansing, Michigan. https://www.canr.msu.edu/resources/seed-selection-cost-comparison-decision-tool (accessed 4 Jun 2024)

Larson JE, Agneray AC, Boyd CS, Bradford JB, Kildisheva OA, Suding KN, Copeland SM (2023) A recruitment niche framework for improving seed-based restoration. Restoration Ecology 31:e13959. https://doi.org/10.1111/rec.13959

Laughlin D, Chalmandrier L (2018) Select: determines species probabilities based on functional traits. https://cran.r-project.org/web/packages/Select/index.html (accessed 4 Jun 2024)

León-Lobos P, Bustamante-Sánchez MA, Nelson CR, Alarcón D, Hasbún R, Way M, Pritchard HW, Armesto JJ (2020) Lack of adequate seed supply is a major bottleneck for effective ecosystem restoration in Chile: friendly amendment to Bannister et al. (2018). Restoration Ecology 28:277–281. https://doi.org/10.1111/rec.13113

Li YM, Gornish ES (2020) General attributes and practice of ecological restoration in Arizona and California, U.S.A., revealed by restoration stakeholder surveys. Restoration Ecology 28:1296–1307. https://doi.org/10.1111/rec.13221

Liu U, Cossu TA, Dickie JB (2019) Royal Botanic Gardens, Kew's Seed Information Database (SID): a compilation of taxon-based biological seed characteristics or traits. Biodiversity Information Science and Standards 3:e37030. https://doi.org/10.3897/biss.3.37030

Massatti R, Shriver RK, Winkler DE, Richardson BA, Bradford JB (2020) Assessment of population genetics and climatic variability can refine climate-informed seed transfer guidelines. Restoration Ecology 28:485–493. https://doi.org/10.1111/rec.13142

Matzek V, Covino J, Funk JL, Saunders M (2014) Closing the knowing–doing gap in invasive plant management: accessibility and interdisciplinarity of scientific research. Conservation Letters 7:208–215. https://doi.org/10.1111/conl.12042

McCormick ML, Carr AN, Massatti R, Winkler DE, De Angelis P, Olwell P (2021) How to increase the supply of native seed to improve restoration success: the US native seed development process. Restoration Ecology 29:e13499. https://doi.org/10.1111/rec.13499

Meredith GR, Brunson MW, Hardegree SP (2021) Management innovations for resilient public rangelands: adoption constraints and considerations for interagency diffusion. Rangeland Ecology & Management 75:152–160. https://doi.org/10.1016/j.rama.2021.01.002

NASEM (National Academies of Sciences, Engineering, and Medicine) (2023) An assessment of native seed needs and the capacity for their supply: final report. The National Academies Press, Washington, D.C. https://doi.org/10.17226/26618

National Academies of Sciences, Engineering, and Medicine (2020) An assessment of the need for native seeds and the capacity for their supply: interim report. National Academies Press, Washington, D.C.

Nerlekar AN, Sullivan LL, Brudvig LA (2024) Grassland restorations must better foster forbs to facilitate high biodiversity. Restoration Ecology 32:e14214. https://doi.org/10.1111/rec.14214

Pearman O, Cravens AE (2022) Institutional barriers to actionable science: perspectives from decision support tool creators. Environmental Science & Policy 128:317–325. https://doi.org/10.1016/j.envsci.2021.12.004

Pilliod DS, Welty JL, Jeffries MI, Schueck LS, Zarriello TJ (2018) Land treatment exploration tool (rev. 1.3, March 2023): U.S. Geological Survey Fact Sheet 2018-3042, 2. https://doi.org/10.3133/fs20183042.

Pywell RF, Bullock JM, Roy DB, Warman LIZ, Walker KJ, Rothery P (2003) Plant traits as predictors of performance in ecological restoration. Journal of Applied Ecology 40:65–77. https://doi.org/10.1046/j.1365-2664.2003.00762.x

Rayome D, DiManno N, Ostertag R, Cordell S, Fung B, Vizzone A, Pante P, Tate R (2019) Restoring Ecosystem Services Tool (REST): a program for selecting species for restoration projects using a functional-trait approach. General technical report PSW-GTR-262. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station 47, Albany, California

Schohr TK, Gornish ES, Woodmansee G, Shaw J, Tate KW, Roche LM (2020) Practitioner insights into weed management on California's rangelands and natural areas. Environmental Management 65:212–219. https://doi.org/10.1007/s00267-019-01238-8

Seed-Spec (n.d.) Seed-Spec selection tool (southwest/southern United States). https://seedspec.com/ (accessed 4 Jun 2024)

Shackelford N, Paterno GB, Winkler DE, Erickson TE, Leger EA, Svejcar LN, et al. (2021) Drivers of seedling establishment success in dryland restoration efforts. Nature Ecology & Evolution 5:1283–1290. https://doi.org/10.1038/s41559-021-01510-3

Shaw N, Barak RS, Campbell RE, Kirmer A, Pedrini S, Dixon K, Frischie S (2020) Seed use in the field: delivering seeds for restoration success. Restoration Ecology 28:S276–S285. https://doi.org/10.1111/rec.13210

Shryock DF, DeFalco LA, Esque TC (2022) Seed Menus: An integrated decision-support framework for native plant restoration in the Mojave Desert.. Ecology and Evolution 12(4):e8805. https://doi.org/10.1002/ece3.8805

Shryock DF, DeFalco LA, Esque TC (n.d.) Mojave seed menus: a new spatial tool for restoration software release v1.0. USGS Science for a Changing World. https://

www.usgs.gov/software/mojave-seed-menus-a-new-spatial-tool-restoration-software-release-v10 (accessed 4 Jun 2024)

Society for Ecological Restoration (n.d.) SER standards tools. https://www.ser.org/page/Standards-Tools (accessed 4 Jun 2024)

Society for Ecological Restoration, International Network for Seed Based Restoration, Royal Botanic Gardens Kew (2023) Seed Information Database (SID). https://ser-sid.org/

St. Clair JB, Richardson BA, Stevenson-Molnar N, Howe GT, Bower AD, Erickson VJ, Ward B, Bachelet D, Kilkenny FF, Wang T (2022) Seedlot selection tool and climate-smart restoration tool: web-based tools for sourcing seed adapted to future climates. Ecosphere 13:e4089. https://doi.org/10.1002/ecs2.4089

State of California (n.d.) TransPlant seed plant calculator (California, U.S.A.). CalTrans. https://dot.ca.gov/programs/design/lap-seed-plant-calculator-transplant (accessed 4 Jun 2024)

Stewart J, Zhao Y, Wright J (n.d.) The Climate-Adapted Seed Tool (CAST). Reforestation tools. https://reforestationtools.org/climate-adapted-seed-tool/

Svejcar T, Boyd C, Davies K, Hamerlynck E, Svejcar L (2017) Challenges and limitations to native species restoration in the Great Basin, U.S.A. Plant Ecology 218:81–94. https://doi.org/10.1007/s11258-016-0648-z

Texas A&M University-Kingsville (n.d.) Native seed selection tool. Caesar Kleberg Wildlife Research Institute, Kingsville, Texas. https://ckwri.tamuk.edu/research-programs/texas-native-seeds-program-tns/native-seed-selection-tool (accessed 4 Jun 2024)

United States Department of Agriculture and U.S. Federal Highway Administration (2017) National database for pollinator-friendly revegetation and restoration. http://www.nativerevegetation.org/era/ (accessed 4 Jun 2024)

U.S. Department of Energy (n.d.) Phase seed selection tool. PHASE – Pollinator Habitat Aligned with Solar Energy. https://phase.erc.uic.edu/SeedSelection (accessed 4 Jun 2024)

University of Arizona (n.d.) EcoRestore Arizona—Native Plant Species Finder Tool (Arizona, U.S.A.). EcoRestore Portal Restore Arizona's Native Plants. https://ecorestore.arizona.edu/

University of Illinois Chicago and Stantec (n.d.) Phase Cost Comparison Tool. PHASE – Pollinator Habitat Aligned With Solar Energy. https://phase.erc.uic.edu/CostComparison

Uprety Y, Asselin H, Bergeron Y, Doyon F, Boucher JF (2012) Contribution of traditional knowledge to ecological restoration: practices and applications. Ecoscience 19:225–237. https://doi.org/10.2980/19-3-3530

Utah State University (n.d.) EcoRestore Utah—Native Plant Species Finder Tool (Utah, U.S.A.). Utah State University EcoRestore Utah Portal Extension. https://extension.usu.edu/ecorestore/ (accessed 4 Jun 2024)

Vitt P, Finch J, Barak RS, Braum A, Frischie S, Redlinski I (2022) Seed sourcing strategies for ecological restoration under climate change: a review of the current literature. Frontiers in Conservation Science 3:938110. https://doi.org/10.3389/fcosc.2022.938110

Walker KJ, Stevens PA, Stevens DP, Mountford JO, Manchester SJ, Pywell RF (2004) The restoration and re-creation of species-rich lowland grassland on land formerly managed for intensive agriculture in the UK. Biological Conservation 119:1–18. https://doi.org/10.1016/j.biocon.2003.10.020

Wang C, Jian S, Ren H, Yan J, Liu N (2021) A web-based software platform for restoration-oriented species selection based on plant functional traits. Frontiers in Ecology and Evolution 9:570454. https://doi.org/10.3389/fevo.2021.570454

Yazzie JO, Fulé PZ, Kim YS, Sánchez Meador A (2019) Diné kinship as a framework for conserving native tree species in climate change. Ecological Applications 29:e01944. https://doi.org/10.1002/eap.1944

Supporting Information

The following information may be found in the online version of this article:

Table S1. A rating of the usability of seed-based restoration tools for practitioners.

Coordinating Editor: Paul Nevill

Received: 3 July, 2024; First decision: 12 August, 2024; Revised: 30 December, 2024; Accepted: 10 March, 2025