How to increase the supply of native seed to improve restoration success: the US native seed development process

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With the United Nations Decade on Ecosystem Restoration, restoration of damaged ecosystems is turning into a global movement. Restoration actions that are not based on science and an understanding of ecosystem function can thwart desired restoration outcomes at best and cause further damage to ecosystems at worst. Restoration often includes revegetation using seed. Where we source seed for restoration can make a difference for species establishment, restoration outcomes, and recovery of ecosystem function. However, sourcing seeds of native species, let alone genetically appropriate seed, is not currently possible for many restoration projects. The process of increasing and sourcing suitable seed for restoration includes many steps that need to be addressed typically years before a restoration project is initiated. These steps of seed collection, evaluation and development, field establishment, production, certification and procurement, storage, and finally restoration, need to be considered ideally at a scale larger than individual restoration projects and with research conducted in each step. We describe these steps as implemented in the United States, the challenges therein, and provide suggestions and examples of how groups can make efficient and effective progress toward getting the right seed in the right place at the right time.

Key words: native seed supply chain, native plant materials, seed market, seed supply, seed-based restoration

Implications for Practice
- Restoration success is supported by the availability of native seed that represents both species and genotypic diversity.
- The Native Plant Materials Development Process (the Development Process) effectively addresses the need to increase native seed supplies and serves as a simplified model for converting wildland-collected native seed into a native seed crop for use in restoration projects.
- To be successful, the Development Process requires long-term collaboration, funding, research, and strategic planning.
- The Development Process can be modified for implementation at any scale in any part of the world, offering a tangible example to aid the action plan for the United Nations Decade on Ecosystem Restoration.

Introduction
Successful restoration of degraded ecosystems is fostered by using genetically appropriate seed and other native plant materials (hereafter, “seed”), which are adapted to the environmental conditions and ecological relationships of the restoration site (Johnson et al. 2010), and thus are more likely to establish, persist, and support resilient communities (Bucharova et al. 2021; Nef et al. 2021). However, restoration practitioners often use the most affordable and easily accessible seed (NASEM 2020). Opportunistic sourcing of seed may result in the use of nonnative species or native species that are not biologically or genetically appropriate for a given restoration site. This can result in further degradation caused by...
introduction of an invasive or weedy species, a reduction in biodiversity, lack of revegetation success, and/or an inability to meet long-term management objectives (Baughman et al. 2019; Ott et al. 2019). The Native Plant Materials Development Process (hereafter, the Development Process) represents an example of a cross-cutting suite of activities that coordinates the development of native seed for restoration (Fig. 1; Table 1). First described in a U.S. Bureau of Land Management (BLM) report to the U.S. Congress (BLM 2009), the Development Process is a strategic, adaptable model that links diverse stakeholder groups, including government agencies (federal, tribal, state, and local), academic institutions, private industry (e.g. plant nurseries, plant producers, utility and mining companies), nonprofit groups, and the general public. The Development Process targets high-priority restoration species and not those that are rare, threatened, or endangered. Here, we describe the Development Process and highlight connections among the steps; identify challenges and considerations; and highlight examples of work being done in the United States. As the United Nations Decade on Ecosystem Restoration catalyzes restoration of degraded landscapes, our goal is to illustrate a successful framework for native seed development and use that promotes desirable restoration outcomes, biodiversity, and ecosystem function.

Steps of the Development Process

Seed Collection

Collection of native seed from wildland plant populations represents the genetic diversity and variability from which seed can be produced for restoration. As such, without comprehensive effort to collect seed that represent species’ range-wide variabilities, desirable restoration may not be achieved (Havens et al. 2015; Nef et al. 2021). Developing a repository of seed collections requires funding, time, and collaboration across a variety of agencies, partners, and individuals. Project planning is critical for seed collection (Cross et al. 2020; Pedrini et al. 2020). Depending on funding and program goals, collection efforts must strategically prioritize the number of species, number of collections, and the size of collections. One option is to stratify collection efforts to represent interspecific and intraspecific diversity by collecting as many species and populations as possible. This approach enhances biological and genetic diversity and supports finer scale research and development but may result in collections that are too small for other steps in the Development Process (Nef et al. 2021). Alternatively, fewer species and/or larger collections decrease curation and storage costs at the expense of potentially missing collateral opportunities (e.g. Hoban et al. 2013 for conservation genetics; Greene et al. 2019 for crop wild relatives; Barga et al. 2020 for predisturbance collections). Seed collection teams should keep in mind challenges imposed by natural factors such as year-to-year weather variability and species phenology that affect seed development in wild populations. For example, multiple trips to collection sites are required to obtain enough ripe seed for many species, which is a challenge for remote collection locations. Further, collections should include seed from edge or less than ideal habitats or in years when conditions are relatively unfavorable for seed production because seed produced under these scenarios may be important for genetic diversity and adaptation to climate change (Havens et al. 2015).

Collection from wild populations is just one part of this step. Before collection, permissions must be obtained from the land manager or owner. During collection, voucher specimens to verify identity and location data need to be collected, and these data should remain with the seed throughout the Development Process. Also, collectors should follow science-based protocols to obtain a genetically diverse collection and not overharvest. Seeds of Success, a national native seed collection program in the United States, provides standard protocols and datasheets for seed collection of restoration species (Haidet & Olwell 2015; BLM 2018). After collection, seeds must be dried, cleaned, tested, and properly stored (De Vitis et al. 2020; Frischie et al. 2020). Such complexities highlight the need for consistency in the management of a seed collection program so that a high-quality, curated seed inventory can be achieved.

Evaluation and Development

Evaluation and development in the form of scientific research and information gathering ultimately guide the selection of species and their sources. Research in this step facilitates understanding of basic...
Table 1. The Native Plant Materials Development Process includes seven steps. It was originally defined in 2009 by the Bureau of Land Management (BLM), an agency in the U.S. Department of Interior (BLM 2009). We have expanded upon the original description for use more broadly by any group wanting to increase supply of seed and improve restoration. Each step contains its own set of considerations that should be addressed for progress on that step to be made. We have included exemplary programs, projects, or businesses that can be used as models. References listed explain the step in more detail.

| Definition of the Step                                      | Key Issues, Complexities, and Challenges                                                                 | Examples                                                                 | References                                      |
|-------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|-------------------------------------------------|
| Seed collection: Harvesting seeds from wild populations      | Selecting priority species and ecotypes in coordination with seed users and growers.                    | Seeds of Success                                                        | Pedrini et al. 2020                              |
|                                                             | Strategy for sourcing seed given a species’ population dynamics and climate change.                      | Hawai’i Seed Bank Partnership                                            | Gann et al. 2019, appendix 1                     |
|                                                             | Use of science-based collection procedures, including collection of voucher specimens and field data that | Chicago Botanic Garden’s Dixon National Tallgrass Prairie Seed Bank     | Nevill et al. 2018                               |
|                                                             | should remain with the seed throughout the Development Process.                                        |                                                                          |                                                 |
|                                                             | Ethical and legal challenges of collecting wild seeds including who owns the collected seed.            |                                                                          |                                                 |
| Evaluation and development: Research into basic life history traits that influence the successful use of native seed in restoration | Complexities of managing knowledge gaps and need for restoration actions.                                 | Fort Bellnap Native Seed and Grassland Restoration Program              | Haidet & Olwell 2015 Ten Kate & Laird 1999      |
|                                                             | For example:                                                                                             | Climate-Smart Restoration Tool                                          | Erickson & Halford 2020                         |
|                                                             | Seed transfer zones updates can complicate planning                                                    | USGS Genetics for Western Restoration and Conservation Program           | Havens et al. 2015                              |
|                                                             | Identifying candidate species for development can take years; seed collection teams are on the ground today | Great Basin Research Center and Native Plant Project                     | Bower et al. 2014                               |
| Field establishment: Development of native seed production protocols and seed stock by the agricultural science community | Developing growing protocols and specialized equipment for harvest, including protocols that maintain genetic diversity of wild populations. | USDA-NRCS Native Seed Production Manual for the Pacific Northwest (Bartow 2015) | Erickson & Halford 2020                         |
|                                                             | Testing candidate species for applicability for production requires long-term commitment and may not be successful. | Western Forbs: Biology, Ecology, and Use in Restoration (Gucker & Shaw 2020) | Basey et al. 2015                               |
|                                                             | Texas Natives ProgramOregon State University Malheur Experiment Station                                 |                                                                          |                                                 |
| Seed production: Farming of seed for restoration             | Growing native seed as crops is risky: not eligible for crop insurance; can take years to produce a yield; fields may not produce a reliable crop; no guaranteed demand for crop | Madrean Archipelago Plant Propagation Center                           | Pedrini et al. 2020                              |
|                                                             | Operationalizing at a scale useful for restoration and procurement (like within a seed transfer zone)    | USDA-USFS National Reforestation, Nurseries, and Genetic Resources (RNGR) Program | Dumroese et al. 2009                            |
|                                                             | Developing growing techniques for unique situations including multiple species in a single field, woody species orchards, tissue cultivation, and nonvascular plant production | Commercial seed companies such as BFI Native Seeds LLC                  |                                                 |
|                                                             |                                                                          | Sagebrush in Prisons Project                                             |                                                 |

(Continues)
| Definition of the Step                                                                 | Key Issues, Complexities, and Challenges                                                                 | Examples                                                                 | References                          |
|---------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|-------------------------------------|
| Seed certification and procurement: Cleaning, testing, labeling, and purchasing genetically appropriate seed | Collaboration needed across many seed users and producers at an eco-regional scale                        | Association of Official Seed Certifying Agencies                        | Erickson & Halford 2020             |
|                                                                                       | Planning is critical and can improve availability: need for seed users to develop prediction lists of species and genotypes 5–10 years out | Association of Official Seed Analysts                                   | Camhi et al. 2019                   |
|                                                                                       | Seed certification for native plants not always available, sufficient, or required                       | Federal agency consolidated seed buys                                  | White et al. 2018                   |
|                                                                                       | Native seed testing protocols complicated by inter- and intraspecific genetic and geographic variability in life history traits | Nevada Native Seed Partnership                                          |                                     |
|                                                                                       | Building more botanical and ecological expertise on recovery project teams is needed, including project preplanning and disaster preparedness so that plants are no longer a last-minute consideration | NW Minnesota Native Prairie Seed Consortium USDA-NRCS National Laboratory for Genetic Resources Preservation |                                     |
| Seed storage: Seed banking, including short-term storage for active use and long-term storage for conservation | Cleaning and storage protocols needed for each species which may require specialized equipment         | BLM and USDA-USFS seed warehouses                                       | De Vitis et al. 2020               |
|                                                                                       | Understanding longevity and viability for species being stored still largely unknown                    | USDA-ARS National Plant Germplasm System                               | Frischie et al. 2020               |
|                                                                                       | Building techniques for storing nonorthodox materials and seed needed (e.g. living tissue or seed from genera *Quercus* and *Salix*) | USDA-ARS National Laboratory for Genetic Resources Preservation         | Pedrini & Dixon 2020               |
|                                                                                       | Seed cleaning and long- and short-term storage facilities are inadequate to match need                  |                                                                        | Merritt & Dixon 2011 Dumroese et al. 2009 |
| Restoration: Rebuilding native plant communities for functioning, resilient ecosystems, including research on restoration practices | Building research on techniques needed to improve restoration outcomes *by ecoregion*, including species-specific techniques | Restoration Handbook for Sagebrush Steppe Ecosystems (Pyke et al. 2017) | Pedrini et al. 2020               |
|                                                                                       | Monitoring needed to track outcomes by ecoregion and inform adaptive management                         | USGS Restoration Assessment and Monitoring Program for the Southwest (RAMPS) | Shaw et al. 2020                   |
|                                                                                       | Developing tools and seed menus to aid project managers in selecting and assembling species mixes       | USGS and BLM Land Treatment Exploration Tool                            | Oldfield et al. 2019               |
|                                                                                       | Developing proactive and strategic restoration strategies given climate change and need for functional habitat connectivity | International Network for Seed-Based Restoration                      | Bradford et al. 2018               |
life history for native species, including germination and pollination requirements, seed transfer zones (i.e., where to source and use seed), and the identification of species as ecosystem “workhorses” or essential for restoration (Havens et al. 2015). As more is understood about seed biology, including genetic and geographic variability, restoration professionals are better able to grow the species and develop a consistent source of seed (Topping et al. 2019), as well as successfully use seed in restoration treatments. Common garden studies are typically utilized to identify adaptive trait variation and develop guidance regarding the environmental suitability of seed for restoration sites (Johnson et al. 2017; Richardson & Chaney 2018; Germino et al. 2019). Furthermore, trait-based approaches in the field or greenhouse may identify adaptive variation hidden in other experimental designs (e.g., Roybal & Butterfield 2019). Newer technologies, such as next-generation sequencing genetic techniques, may also support the creation of seed transfer zones that not only match species’ patterns of adaptation to present and future landscapes (e.g., Shryock et al. 2020), but can protect natural patterns of genetic diversity (Massatti & Knowles 2020).

Sustained research is required to increase the breadth of species available, the diversity of sources representing each species, and guidance for how best to use seed in current and future climates. This problem is complex, as it not only necessitates knowing how existing seed should best be used to protect intrinsic biodiversity and promote successful restoration outcomes, but it requires that we understand patterns of genetic diversity, species’ adaptations to their environments, and even interactions among members of biological communities (Bucharova et al. 2021). In addition, there are still many species for which field establishment, production, and harvesting research may drive cost-effective development, thus making those species suitable for widescale restoration (e.g., Simonson & Tilley 2016). None of these challenges are beyond the capabilities of the researchers and professionals like those who currently contribute to the Development Process, if research efforts are consistently supported, and participants actively share progress and achievements.

Field Establishment

Field establishment is a transitional step between wild collection and production of seed for the commercial market. In this part of the Development Process, the agricultural scientific community conducts research and provides guidance for the commercial production of native seed (e.g., row spacing, harvest methods, pest control). Field establishment can take 3–5 years, during which production protocols and stock sources of seed are developed with the goal of distributing seed and technical assistance to commercial growers (Erickson & Halford 2020; Tangren & Toth 2020). Genetic research is also needed in this step to ensure genetic diversity and desired adaptations are not compromised throughout the development process, given that supplemental irrigation, planting methods, and changes in environmental conditions can alter seed performance. Progress on developing new native seed crops is made slowly, one species at a time. Regional partnerships can provide support needed for developing new materials and technical assistance for growers and restoration practitioners specific to ecosystems in a region (i.e., Gucker & Shaw 2020).

Seed Production

Production involves growing restoration species in agricultural settings to produce seed in quantities necessary for landscape-scale restoration. This is often conducted by farmers or agricultural producers in partnership with end-users. Many producers already grow native cultivars, and some produce source-identified native seed (i.e., those with certified origin and ecotype information associated with them), but to meet the increasing demand for genetically appropriate seed, more producers need to become involved. This step requires innovation, financial investment, and long-term partnership.

Beyond lag time from starting a production field to harvesting a seed crop, producing seed can be a risky investment for agricultural producers. Seed is generally grown on speculation, or with the hope that it can later be sold. The risk is due to volatilities of the seed market (see seed certification and procurement); the predictable uses of seed are often not enough to sustain ongoing production of genetically appropriate seed as costs fluctuate due to demand; and these seeds are generally more expensive compared to cultivars and nonnatives used for restoration and landscaping (Camhi et al. 2019; Tangren & Toth 2020). The National Academies of Sciences, Engineering, and Medicine’s (NASEM) is currently conducting a national assessment of the need for native seeds and the capacity for their supply (www.nas.edu/seedneeds) to further identify causes of and provide recommendations for seed market volatility and other native seed supply issues (NASEM 2020).

Two potential market-strengthening solutions currently being implemented involve subsidizing the development of new native species as crops and establishing cooperative regional seed partnerships. For example, the BLM uses specialized contracts (indefinite delivery, indefinite quantity) to reduce risks to growers by providing a minimum payment that does not require a yield. With seed production costing an average of $10,000 per acre (Ollwell & Bosak 2015), these contracts cover initial costs that would otherwise be absorbed by growers. An example of a successful seed partnership is the Willamette Valley Native Plant Partnership, which produced 213 kg of seed in 7 years (Currin & Larsen 2019). The group is now able to transition from funding via partner contributions to funding operations through sales.

Seed Certification and Procurement

To ensure the successful use of genetically appropriate seed in restoration projects, seed should be cleaned and tracked from collection to procurement. Seed cleaning involves extracting pure live seed from inert material (e.g., soil, stems, leaves) that is often incidentally harvested along with seed (Herriman 2017). Tracking seed typically involves a seed certification program that includes source identification, origin validation, viability testing, and purity testing (Pedrini & Dixon 2020). However, the requirement for seed certification varies among federal and state agencies and among countries, which impedes the development and adoption of a standard certification protocol. Moreover, native plants have diverse life histories, and germination requirements can differ within a species.
across its range, imposing difficulties on the certification process (Frischie et al. 2020; Walter 2020). Native seed testing protocols need to be expanded to include the diversity of species used in current and future restoration projects. This will require protocol development by seed analysts and certifiers.

Procurement is the process of getting agriculturally produced seed into the hands of restoration practitioners. This step can take years of planning and can be facilitated by decision-support tools for selecting and purchasing native seed (e.g. Howe et al. 2009). In the United States, federal agencies are the largest buyers of native seed, and federal procurement regulation (Federal Acquisition Regulation) has a strong effect on all aspects of the Development Process (NASEM 2020). Agencies often partner on consolidated buys, which are centralized bulk purchases of commercially produced seed, with quantities selected based on anticipated needs or in emergency response to events like wildfires. The amount purchased can vary substantially year-to-year due to the unpredictability of weather- and climate-related disturbance events. For example, BLM purchases on average 907,000 kg of seed annually, but that quantity ranges from 136,000 to 3,400,000 kg (BLM National Seed Warehouse System, 2020, personal communication). Large purchases can deplete stocks of seed for other users, while small purchases may result in seed surpluses. Collaborative procurement policies that span multiple years and improve storage and processing capacity can help stabilize market volatility (Erickson & Halford 2020).

**Seed Storage**

Seed storage is the most efficient and cost-effective method of conserving native plant germplasm for future use and maintaining seed viability during storage is critical to restoration success. Seed can be stored for as little as 3 months to hundreds of years, depending on the species and type of material (e.g. orthodox versus recalcitrant seed; Hay & Sershen 2020, Walters & Pence 2020), as well as fluctuations in and achievement of ideal moisture, temperature, and oxygen at the storage facility (De Vitis et al. 2020). Cold, dry conditions facilitate long-term storage of orthodox seeds, whereas ambient conditions (e.g. in many seed warehouses) are often suitable if seeds are used within 1 or 2 years after collection. The Food and Agriculture Organization of the United Nations maintains detailed standards and best practices for the storage of seed and other plant materials (FAO 2014).

Storage occurs across sectors and timeframes. For example, the Chicago Botanic Garden stores more than 4,000 accessions of native seed from more than 1,700 species in their Dixon National Tallgrass Prairie Seed Bank (Chicago Botanic Garden 2021). Seeds of Success collections go into both long-term conservation storage and short-term storage for use in research and current restoration projects. Increasing the capacity of cold and frozen seed storage allows practitioners to plan for future restoration projects, to respond quickly to events requiring emergency stabilization and rehabilitation, and to stabilize the demand for commercially produced native seed (Merritt & Dixon 2011; NASEM 2020).

**Restoration**

The ultimate goal of the Development Process is to support restoration of native plant communities, and the previous steps enable and enhance these efforts through the development of genetically appropriate native seed. As a result, the Development Process facilitates restoring ecosystem services, rebuilding wildlife habitat, reclaiming mined areas, maintaining biodiversity, and developing usable information to foster collaboration and knowledge sharing across systems. Restoration includes not only wild and managed public lands, but also designated wildlife corridors, roadsides, county landfills, highway embankments, coastal shipping areas, military training grounds, and urban parks, to name a few. As such, practitioners come from diverse backgrounds. Regardless of practitioner experience, there is a clear need to continually learn and update what we know about which is the right species (e.g. Rayome et al. 2019), where is the right place (e.g. Germino et al. 2019), when is the right time (Bradford et al. 2018), which methods or techniques are most cost-effective (e.g. Munson et al. 2020), how we can utilize future climate projections to avoid restoration failure (e.g. Richardson & Chaney 2018), and how we can remove barriers to traditional land stewardship activity (Long & Lake 2018). Posttreatment monitoring of restoration sites is an essential, yet uncommon, component of restoration (Herrick et al. 2006; Copeland et al. 2018). Knowledge of native seed performance and restoration success can be utilized to inform future native seed development and support restoration strategies.

**Putting It All Together**

Cross-sector collaboration among diverse stakeholders is critical for increasing the diversity and quantity of seed (Fig. 2). There are many approaches that vary according to funding source, policy, and regional scale. An example of a successful effort is the Iowa Ecotype Project (www.tallgrassprairiecenter.org). Catalyzed by a policy change in 1988 that emphasized native seed in roadway projects, it now provides native prairie seed to public and private restoration projects across four U.S. states. The project began by increasing seeds for three species commonly used in prairie restoration and grew to develop an additional three to four species per year. They currently have a catalog of 145 sources representing 80 species grown by 19 producers and have developed a seed certification program. Together, these efforts have culminated in restoration of approximately 425,000 ha of roadsides and private lands (Walter 2020). Iowa Ecotype Project’s 2020 priorities illuminate the iterative nature of the Development Process and its key complexities and challenges (Table 1); they include: increased research on production and restoration; inclusion of cost–benefit analyses and decision support for use of diverse, higher-priced seed; better coordination and communication among partners and buyers of seed to stabilize the market; collaborative research to select new species for development and update seed transfer zones; and improvement of seed testing and certification (Walter 2020).
Communication among stakeholders is necessary across all steps of the Development Process. Seed collectors need to know which species are needed by seed users, who optimally understand what species are suitable for agricultural production. Similarly, those in charge of seed procurement, regardless of project scale or duration, should have botanical knowledge and must have access to updated seed inventories. Finally, the entire Development Process needs to be supported by research and local and indigenous knowledge on which species to choose and where to place them. The Development Process represents the culmination of decades of work by researchers and producers, but it must be continuously updated as science and practice improve our understanding of seed development (Basey et al. 2015; Jones 2019). We acknowledge that it can be difficult to know when to advance efforts along the Development Process and when to wait for further guidance from research. The benefits and drawbacks of using available seed, even if suboptimal, should be weighed with every project.

More than 70 countries signed the resolution proclaiming 2021–2030 to be the UN Decade on Ecosystem Restoration (United Nations General Assembly 2019), which implies that at least 70 countries need a strategic plan for developing supplies of seed. Several nations have recognized this need and are making progress (Ladouceur et al. 2017; León-Lobos et al. 2020; Vidal et al. 2020). Not all countries—or projects within the same country—have the same infrastructure or needs (societal or ecological), meaning that restoration practitioners must operate along a continuum of restorative activities to apply the most appropriate and effective treatment for their particular context (Gann et al. 2019). Although there is not one best way for restoration to proceed, we hope that illustrating the Development Process can provide inspiration and direction to developing programs where and when needed. Ultimately, any program whose goals encompass ecosystem restoration must put the right seed in the right place at the right time.

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