

PRACTICAL ARTICLE

Collection and production of native seeds for ecological restoration

Simone Pedrini^{1,2} , Paul Gibson-Roy³ , Clare Trivedi⁴, Candido Gálvez-Ramírez⁵, Kate Hardwick⁴, Nancy Shaw⁶ , Stephanie Frischie⁷ , Giles Laverack⁸, Kingsley Dixon¹ 

The global push to achieve ecosystem restoration targets has resulted in an increased demand for native seeds that current production systems are not able to fulfill. In many countries, seeds used in ecological restoration are often sourced from natural populations. Though providing seed that is reflective of the genetic diversity of a species, wild harvesting often cannot meet the demands for large-scale restoration and may also result in depletion of native seed resources through over harvesting. To improve seed production and decrease seed costs, seed production systems have been established in several countries to generate native seeds based on agricultural or horticultural production methods or by managing natural populations. However, there is a need to expand these production systems which have a primary focus on herbaceous species to also include slower maturing shrub and tree seed. Here we propose that to reduce the threat of overharvest on the viability of natural populations, seed collection from natural populations should be replaced or supplemented by seed production systems. This overview of seed production systems demonstrates how to maximize production and minimize unintended selection bias so that native seed batches maintain genetic diversity and adaptability to underpin the success of ecological restoration programs.

Key words: ethical seed collecting, managed natural plant populations, native seed farm, seed harvesting

Implications for Practice

- Seed collection from natural populations can be used to provide seeds for ecological restoration; however, collection should be performed sustainably to avoid affecting the reproductive capability of the source population.
- Multiplication of native seeds under cultivated production settings should replace or supplement collection from natural populations, whenever feasible, as it reduces impact on natural populations and allows for higher productivity, improved quality, reliability, and reduced seed cost.
- If cultivated production is not feasible, natural populations can be managed to optimize seed production.
- Seed collection and production should aim to avoid active selection for certain traits and limit unintended selection, to maintain the genetic variability of the seed batch.

Introduction

There are three main approaches for supplying native seeds for restoration projects: (1) seed collection from natural/wild populations, (2) harvest from managed populations, and (3) cultivated seed production systems (such as native seed farms). These three seed supply strategies lie along a continuum where increasing inputs are required. The methods present different advantages and limitations and are not exclusive; these sources may be used in complementary and strategic combinations (Fig. 1).

A key aspect of native seed supply for ecological restoration is to adequately capture the genetic diversity representative of a natural population and ensure that such diversity is maintained throughout the supply chain until seeds are deployed to a restoration site (Broadhurst et al. 2008; Erickson & Halford 2020). In recent decades, conservation seed bank initiatives worldwide have developed guidelines and procedures for collecting native seeds in order to adequately capture genetic variability, while avoiding damage to the source populations' reproductive capability (FloraBank 1999; ENSCONET 2009; USDI Bureau of Land Management 2018). These protocols

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¹ARC Centre for Mine Site Restoration, Department of Environment and Agriculture, Curtin University, Kent Street, Bentley, 6102, Western Australia, Australia

²Address correspondence to S. Pedrini, email smnpedrini@gmail.com

³Kalbar Resources, Hay Street, Perth 6000, Western Australia, Australia

⁴Conservation Science Department, Royal Botanic Gardens, Kew, U.K.

⁵Semillas Silvestres, Córdoba, Spain

⁶USDA Forest Service, Rocky Mountain Research Station, 322 E. Front Street, Suite 401, Boise, ID 83702, U.S.A.

⁷Xerces Society for Invertebrate Conservation, Portland, OR 97232, U.S.A.

⁸Scotia Seeds, Brechin DD9 6TR, Scotland, U.K.

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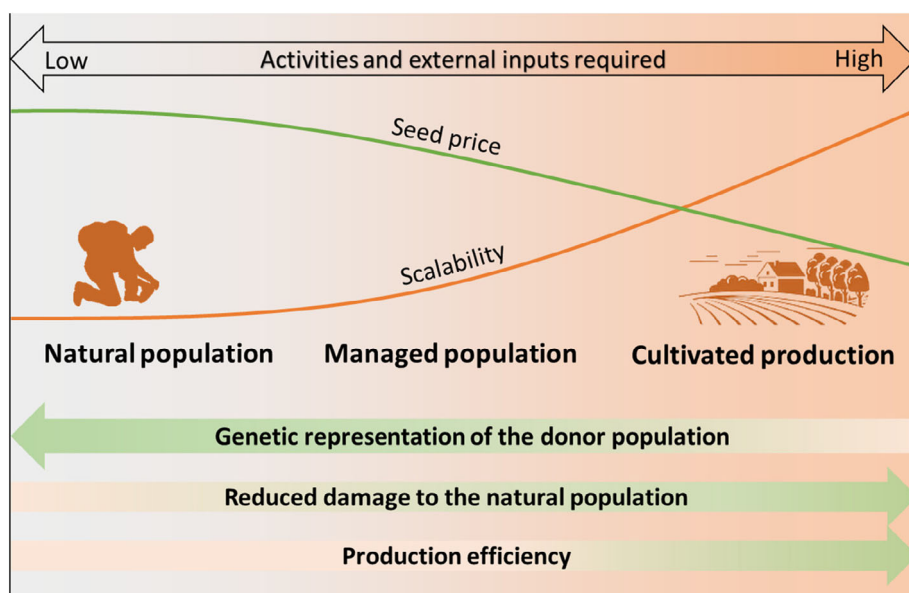


Figure 1. Native seeds supply approaches for ecological restoration. The three approaches commonly used to supply seed for ecological restoration sit on a continuum of increased management activities intensity (e.g. weeding, fencing, plowing, weed mat, sowing). These approaches allow producers to increase seed supply while reducing seed price. Each approach has advantages and disadvantages and might not be always feasible for all species/ecosystems. (Image by Simone Pedrini).

are a useful reference point for planning and collecting seeds for ecological restoration. However, the quantity of seed per collection for conservation purposes is seldom sufficient to meet the demand for native seeds in landscape-scale restoration (Merritt & Dixon 2011) where substantial quantities of seed from large numbers of plants may be harvested (e.g. tens of thousands of plants for mechanical field grass harvest) and so revised collection protocols are required.

However, the rapidly expanding demand for native seed often surpasses the quantity that can be sustainably collected from natural populations (Nevill et al. 2018) where factors such as low or erratic seed set and quality, seed predation, habitat fragmentation, and invasive species all contribute to harvest limitations and increasing seed costs (Broadhurst et al. 2015). Some of these factors can be controlled, or manipulated, by managing natural populations with activities which include weed control, watering, fencing, and fertilization with the aim to improve harvest efficiency and seed yield. This approach can be applied in certain situations or ecosystems (e.g. some tree and shrub species in forest ecosystems, or species-rich grasslands); however, as with seed collection in the wild, such collection volumes requires large areas of relatively intact wild areas to be effective.

The establishment of native seed crops, where seeds are produced in cultivation settings (akin to agricultural or horticultural production), has the potential to meet the rising demand for native seeds (Delpratt & Gibson-Roy 2015; Nevill et al. 2016; Jiménez-Alfaro et al. 2020). Seeds collected from the wild are multiplied using methods and techniques similar to the production of seeds of domesticated cultivars (e.g. cereal crops, fodder species, vegetables, trees for forestry). However, in contrast to traditional farming or horticulture methods, production of native

seeds requires special consideration to avoid, as far as practical, selection of specific traits (Pedrini & Dixon 2020), and to maintain the genetic variation found within natural founding populations as the primary means for ensuring evolutionary and adaptive potential (Basey et al. 2015). Collecting seeds from planted, restored habitats is another alternative, but should be undertaken with caution as the genetic diversity of the restored plant population may be unknown or low. In some cases, suboptimal genetic diversity is mitigated if the restored area is adjacent to remnant natural habitat, thus permitting gene flow from external pollination (Pakkad et al. 2007; Jalonen et al. 2018).

Whenever feasible, collection from natural populations should be replaced or supplemented by production in cultivated settings or managed natural populations, as these sources can provide a reliable and cheaper source of native seed, while limiting potential negative impacts to natural populations.

This article is intended to be an overview of current best practices for the collection and production of native seed and, when read in conjunction with other articles in this special issue (particularly genetic considerations in seed sourcing as reviewed by Erickson and Halford (2020), provides the framework for improving our understanding of the seed supply chain.

Seed Collection From Natural Populations

The native seed supply chain commences with the collection of seeds from natural populations.

Collection can be used as a foundation for seed multiplication in cultivated seed production systems, to enrich managed natural populations or for deployment to a restoration site via direct seeding (Broadhurst et al. 2008). When collecting from the wild,

the two overriding concerns are: (1) to avoid negative impacts on the native donor population and (2) to retain appropriate genetic diversity of the donor population.

Pre-Planning

Considered and cautious pre-planning is a key requisite for achieving high-quality, well-documented seed collections. Prior to collecting seed from natural populations, it is important to obtain information on a species biology (e.g. breeding system, estimated flowering and fruiting dates) and likely distribution. Depending on identified project needs/strategies, seed may be collected from one or many natural donor sites, and these need to be identified in advance. Locating appropriate donor sites may require investigating national or local seed herbarium records and botanical or forestry databases, and dialogue with experts (local or otherwise) and other seed collectors. Avoid, or be cognizant of, planted populations where vegetation is of unknown or inappropriate origin. Before conducting surveys or collections in the field, all required consents and permits must be obtained. As these can take some time to process, permit requests should be submitted in a timely manner to avoid the risk of delays in collection. Collectors must be adequately trained in plant/seed identification and risk assessments should be prepared prior to field-based operations.

Site Surveys

Ideally, donor sites should be surveyed in advance of collection to confirm the location and site attributes (e.g. weed loads, access issues, terrain) and to determine whether adequate plant numbers of each target species are present to provide collections of sufficient quantity and genetic diversity (Way & Gold 2014). If possible, the populations should be monitored from flowering onward to ensure that seed collection dates coincide with seed maturity. However, in many cases, the constant surveillance of a population is impractical due to cost and distance, so collectors should seek additional information from local sources to determine optimum collection times. To optimize quality and longevity, seeds of native species should usually be collected at, or close to, the point of natural seed dispersal. Some species disperse over a very short period, so fruit maturity and weather conditions must be monitored carefully to avoid losing potential harvests (for example, wind-dispersed species like *Eriophorum* spp. may disperse seed rapidly on a windy day). Many other species disperse seed over extended periods and so harvests would be ongoing, to capture variation in traits along different maturity dates (ENSCONET 2009).

Pre-Collection Assessments

Particular care should be taken to avoid over harvesting natural populations, especially for small, rare, endangered, or isolated populations (Broadhurst et al. 2017; Nevill et al. 2018). Aim to carry out a pre-collection assessment immediately prior to collecting, to establish collecting limits. As a

precautionary measure, aim to collect no more than 20% of the seeds that are mature at the time of collection (Way 2003; Pedrini & Dixon 2020) and for multiple collections from the same population, less than 20% of the total seed produced in any 1 year (ENSCONET 2009). For annual species, whose population survival relies on seeds dispersed in any given year, no more than 5–10% of the entire yearly production should be collected, and collection from the same population in consecutive years should be avoided (Meissen et al. 2015). Use the pre-collection assessment to determine the population size (number of plants, plant density), evaluate seed production per plant or area, and obtain an estimate of total seed production, then set the collection goal to be less than the prescribed percentage, as indicated above.

The pre-collection assessment should also estimate seed quality by cut testing a sample of seeds to calculate the percentage of empty or infested seeds, thus estimating the minimum quantity that needs to be collected to achieve the desired number of viable seeds. When wild seed sources are limited, it may be appropriate to collect and store seed over a number of years (under suitable conditions) until sufficient seed is accumulated to initiate the restoration program (DeVitis et al. 2020).

Collection

Collection may involve single or multiple species. A wide range of collection techniques may be used, depending on the target species' phenology and growth form, population size, amount of seed required, and local terrain. Hand-harvesting methods include plucking, stripping, clipping, shaking, and vacuuming, while mechanical methods include brush, vacuum, and combine harvesting. Seeds of tree species are best collected directly from the tree, if possible, as seeds found on the ground may be of low quality (e.g. old, moldy, or insect infested). Collect the seeds into containers/bags that keep the seeds as cool and aerated as possible (Supplement S1). Safety, communication, and biohazard equipment are also essential—useful checklists are provided by Way and Gold (2014) and FloraBank (1999). Appropriate post-harvest management and storage are critical for maintaining seed viability, see DeVitis et al. (2020) and Frischie et al. (2020) for details.

To allow for the optimal, informed use of seed collections, detailed data should be recorded about the seed lot and source population (Supplement S1). Collection of herbarium voucher specimens before or during seed harvest allows for verification of the material collected. The herbarium specimen should include fruits or flowers and bear the same collection number ID as the seed collection.

Seed Collectors

Collection of native seeds from natural populations can be performed by professional seed collectors (Supplement S1), native seed suppliers/producers, restoration contractors, private landowners, public land managers, researchers, conservation seed bank personnel, nonprofit organizations, and



Figure 2. Nödö'u Group in Brazil: Xavante women collecting seeds of Buriti (*Mauritia flexuosa*). The Xavante have a seed-collecting tradition and have participated in the Xingu Seed Network since 2013. (Source: Xingu Seed Network, picture by Rogerio Assis).

volunteers. Inexperienced collectors will require appropriate training and leadership by qualified personnel. The involvement of local indigenous people with intimate knowledge of native species can be invaluable (Fig. 2) while, at the same time, providing important employment opportunities and revenue, thus helping to stabilize seed markets and increasing the reliability of native seed supplies for restoration (de Urzedo et al. 2016, 2019, 2020).

Managed Natural Populations for Seed Production

For some species and ecosystems, seed collection from natural populations can be improved by actively controlling environmental or ecological variables. For example, a population may be managed by removing or controlling unwanted species or encouraging (even planting) the spread of desired plants to achieve larger or more concentrated areas of the target species to be harvested. Management activities can also include irrigation, alteration of nutrient characteristics (e.g. fertilization or biomass removal), reduction of herbivore impacts and managing seed predation (e.g. by fencing, bird netting and other means of deterrence), and imposed disturbance measures (e.g. controlled burning or grazing). These approaches suit some native vegetation systems and land managers better than cultivated seed production. For example, highland areas of Scotland are managed on an ongoing basis to maintain the ideal conditions for animal hunting by arresting the succession to woodland with patch burning on a 15–20 year rotation, encouraging growth of young shoots of heather (*Calluna vulgaris*) and other heathland species (Mallik & Gimingham 1983). This creates large stands of uniform vegetation (often dominated by heather) at the ideal age for seed production allowing collection with a brush harvester.

Managing natural populations can also increase opportunities for sequential harvesting and overall seed yields (e.g. by promoting new growth or extending fruiting periods). A managed natural seed population could be considered and treated similarly to an unmanaged population, especially in terms of phenology, ecology, pollinators, herbivores, and demography. Managed populations (in particular herbaceous species) where

multiple species coexist can be harvested simultaneously (Scotton et al. 2012) to create a mixed species seed mix. Bulk mechanical collection is a common harvest practice for herbaceous ground layer vegetation (i.e. grasses and forbs growing in close association) where these exist in suitable size and quality and on terrain amenable to harvesting (Shaw & Jensen 2014; Gibson-Roy & Delpratt 2015). Mechanical brush or vacuum harvesting is often used as an efficient and effective method for acquiring large seed quantities (especially for grassland and meadow species).

Cultivated Seed Production

Multiplication of native seeds using cultivated production approaches employing agricultural and/or horticultural practices is now an emerging sector in many parts of the world (DeVitis et al. 2017; Gibson-Roy 2018; White et al. 2018; Hancock et al. 2020). The development of cultivated seed production systems, from small-scale container-bed orchards, to large, field-scale farm operations allows for the multiplication of initially small founding collections through to native seed production plots which greatly enhance native seed supply and prevent or reduce impacts of overharvesting from natural populations (Kiehl et al. 2014; Gibson-Roy & Delpratt 2015). Where restoration markets exist to support the high capital outlay (DeVitis et al. 2017; Gibson-Roy 2018; White et al. 2018) installation of seed production areas on former agricultural land can provide ready benefits in terms of suitable terrain, existing infrastructure, and for many herbaceous species, rapid growth and maturity free from competition (Supplement S2). For example, farm production of native seeds for grassland species is comparable to domesticated perennial forage cultivars (e.g. *Lolium perenne*, *Trifolium pratense*) (Mainz & Wieden 2019). Usually, for production at farming scale for native species, a relatively uniform substrate is prepared prior to seeding, and the growing environment is carefully managed to maximize seed production (Fig. 3). Well-planned and implemented cultural practices, such as pruning, biomass manipulation, weed control, irrigation, pest/disease control, and fertilizer applications, are used to promote flowering, facilitate harvesting, and improve yields. In these settings



Figure 3. Seed farms: (A) Field of Wyeth buckwheat (*Eriogonum heracleoides*) in OR, U.S.A. (B) Mechanical sowing of the annual cornflower (*Cyanus segetum*) in Brechin, Scotland. (C) Rows of European native forbs *Achillea millefolium* and *Silene dioica* in Freising, Germany. (D) Planting of *Allocasurina acutivalvis* seedlings into weed mat in Morawa, Western Australia, in an indigenous-owned and operated native seed farm.

native seeds are typically (but not always) directly sown on cleared, tilled, friable seedbeds by purpose built seeding equipment (e.g. placed in rows or surface broadcast). An alternative production system used at small to field scale is to cover bare soil with weed-mat and plant green stock into cut openings (it is also possible to direct sow into the openings for highly germinable species). This approach is effective for a large range of species and functional types (e.g. perennial species, herbaceous or woody) resulting in a major reduction in weed competition while fallen seed can be easily harvested from the weed mat (i.e. sweeping and/or vacuum).

In spite of some similarities in cultural practices, farm-scale native seed production systems differ significantly from those of conventional crop production systems where selection and breeding programs have modified plant and seed traits to achieve specific characteristics that typically include reduced dormancy, increased synchronicity of ripening or shattering, ease of harvest, processing, and storage. These selections result in uniform plants, often with reduced genetic diversity, and with crop production practices that are tailored to maintain this uniformity. Conversely, native seed production systems for use in ecological restoration typically aim to capture and retain a representative and appropriate range of natural genetic variation displayed in founding populations to allow, as much as is possible,

the restored populations to evolve and adapt to prevailing environmental changes (Pedrini & Dixon 2020). With these differences in mind, it is necessary to understand and manage native seed production systems in a way that adopts and modifies relevant agriculture and horticulture systems and equipment to effectively produce native seed of appropriate genetic character and germinability (Supplement S3; Shaw et al. 2012; Shaw & Jensen 2014).

Best Practices to Retain Genetic Diversity

It is important to acknowledge that any seed harvest activity, whether from natural populations (managed or unmanaged) or under cultivated seed systems, may carry the risk of some degree of genetic selection. However, a number of precautions can be taken at each steps of seed procurement to limit, as far as practical, the impact of trait selection.

Collect the Genetic Diversity Representative of a Natural Population

Native seed collection guidelines often recommend that harvest should be made from at least 50 individuals in a population (Brown & Marshall 1995). Recent studies (Hoban & Strand

2015; Hoban et al. 2018) explore the use of simulation models to predict the capture of genetic diversity with different sampling strategies and suggest the adoption of collection guidelines tailored to particular taxa that take into account biological factors such as selfing and seed dispersal strategies.

For taxa with known polyploidy, such as many grasses, it is important (where possible or where the information exists) to determine the ploidy number of the potential source populations and avoid establishing seed production plots with seed from multiple populations with different ploidy levels, because the seed produced by cross fertilization will not produce fertile plants and thus would not persist in restoration plantings (Kramer et al. 2018).

When collecting from natural populations (especially by hand) seeds should be harvested as randomly as possible, avoiding the collection of particular traits, and, if feasible, over several days during the seed dispersal period (The Royal Botanic Gardens Kew 2001; ENSCONET 2009). For large populations of open pollinated species in a uniform landscape, it is often easier to collect in a more systematic way, sampling at regular intervals along a transect or in patterns when using mechanical harvesters to ensure an even contribution of seeds from maternal genotypes.

Guarding Against Genetic and Phenotypic Drift in Cultivated Production

Cultivated native seed production can have the risk of drift in the genetic and phenotypic make-up from the original population due to unintended selection, usually trending towards a narrowing of genetic diversity (Espeland et al. 2017). Native seed producers should be aware of cultural practices that increase the likelihood of active selection for specific traits, for example when growing plants for production (e.g. size, speed of development), at crop harvest (e.g. favoring periods of more synchronous seed set, plant at certain heights, plants with highest yields), or seed processing (e.g. seed shape, size, color) and, as far as practical, take the necessary measures to limit these unintended selection points (Basey et al. 2015). Another practice utilized by seed growers to reduce this risk is by allowing only a defined maximum of generations (e.g. 2–5) before the seed production plot needs to be reseeded with newly collected wild seeds (Gibson-Roy et al. 2010; Association of German Wild Seed and Wild Plant Producers 2017). When tested on five grassland species, this approach proved effective for maintaining the genetic diversity of four species out of five, mostly long-lived and out-breeding perennials, while for *Medicago lupulina*, a short-lived, selfing perennial species, genetic and phenotypic drift was detected after five generations (Nagel et al. 2019). Such studies and results suggest that these

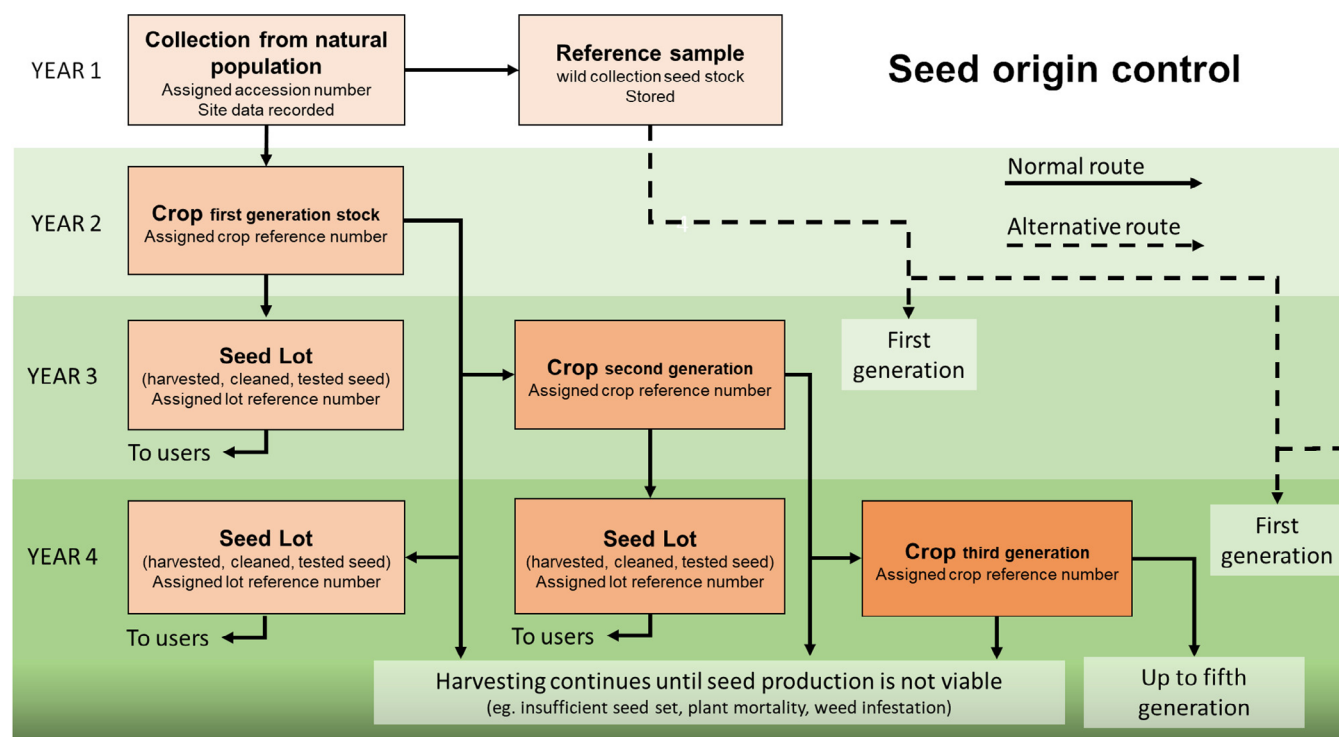


Figure 4. Origin control for seed farm production. All stages are recorded so that seeds can be traced to the original collection. Multiplication of the farm stock should be limited to a maximum five generations from collection. After five generations, a new collection should be made. This graphic is applicable to perennial species that produce seed in the first year. For annual species, harvest of a seed lot is limited to the first year. For perennial and woody species where seed production can occur two or more years after crop establishment, the time scale (on the left) should be extended accordingly. (Original graphic provided courtesy of Scotia Seeds).

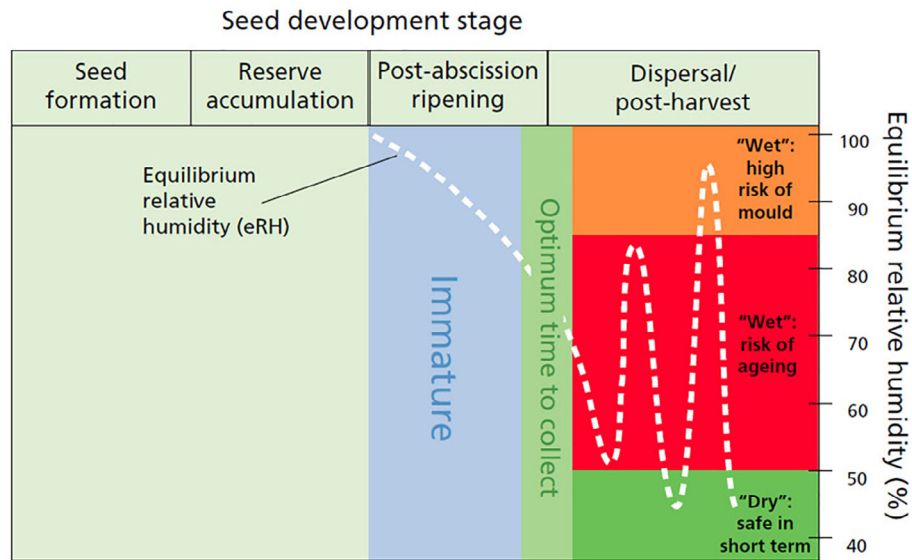


Figure 5. Effect of post-harvest seed moisture status on seed quality. The dashed line shows fluctuations in equilibrium relative humidity with ambient conditions. Copyright 2014 Board of Trustees of the Royal Botanic Gardens, Kew.



Figure 6. Seed collection from natural populations. (A) Seed collecting from *Abies procera*, by U.S. Forest Service climbers in Washington state. Image: M. Way. (B) Collecting tree seed with a pruning pole for RBG Kew's U.K. National Tree Seed Project. (C) Mechanical collection of *Calluna vulgaris* with handheld brush harvester. (D) Vacuum seed harvesting of *Leontodon hispidus*. (Images A,B: Copyright Board of Trustees, RBG Kew. Image C by S. Pedrini. Image D by Marcello De Vitis).



Figure 7. Native seed harvesting machinery. (A) Mini combine harvester. (B) Vacuum harvester from Wildblumenburri in Lenggenwil (Switzerland). (C) Combine harvester and (D) brush harvester used in a hay meadow located in the Pyrenees (Spain). (Pictures (A) and (B) by Simone Pedrini and, (C) and (D) by Candido Gálvez-Ramírez).

approaches are usually effective, but over time and where research and testing capacity are available, the number of generations recommended for cultivated production crops for different taxa (according to life form and reproductive strategies) should ideally be determined on a species by species and region by region basis.

Certification and Traceability

Certification schemes such as the pre-variety germplasm certification program in the United States (Young et al. 2003) or VWV RegioSaaten® in Germany (Mainz & Wieden 2019) are important mechanisms for authenticating the origin of founder seed grown in cultivated seed production settings and that appropriate cultural practices have been adopted in production systems to retain the genetic diversity of those natural founding populations.

Essential to any cultivated native seed production system is a well-structured recording and labelling system that allows for the tracing of a collection from source to field and the path through the production (multiplication) cycle until deployed (Fig. 4). Such systems allow accurate and consistent descriptions of the seed batch through the production cycle. Ideally, they entail recording of essential data to seed growers from source, through cultivation, to harvest yields and seed testing (Guest 2018; Pedrini & Dixon 2020).

Harvesting Techniques and Equipment

Whether seeds are obtained from natural/managed populations or from cultivated seed production systems, similar harvest methodologies and techniques are used; however, the scale of operations, the frequency of harvest, and the volume of seed harvested can be quite different.

Table 1. Comparison of different harvesting methods to be used in managed seed production. *Various hand tools and back-pack or portable vacuum harvesters may be used.

Harvesting Method	Application	Limitations	Species (examples)
Manual*	Small plots to produce foundation seed. Wild populations with limited access. Native stands and planted orchards.	Slow, time consuming. Difficult to harvest large quantities.	All species.
Brush harvester	Species with: Readily dehiscent seed Indeterminate ripening Advantage: multiple harvests possible.	High cost Seed of especially tall or short plants missed.	Grasses. Tall dicots with exposed inflorescences.
Cutting and threshing	Species with: Dehiscence or shattering	Requires significant equipment to manage volume. Cleaning may be difficult, time-consuming, and costly.	Legumes with distinct and rapid dehiscence
Combine harvester	Species with: Short flowering period and indehiscent fruits Easily threshed seeds in favorable seasons Collections of wild populations of some herbaceous species	High fixed and equipment costs. Difficult to use on uneven or steep land. Immature seeds are also collected.	Brassicaceae Asteraceae Plantaginaceae Caryophyllaceae
Vacuum harvester	Species with rapid and fairly uniform dehiscence. Seeds that are: exposed, light, and often possess a coma or pappus. Low-growing or creeping species sown over landscape fabric.	Limited equipment availability. Low collection efficiency.	<i>Nigella</i> spp. <i>Matricaria</i> spp. <i>Trigonella</i> spp. Asteraceae

Ideally, harvest is performed when seeds reach or are near maturity, which is usually the point of natural dispersal. Seeds collected too early may be undeveloped and could lose viability when dried or fail to germinate (Fig. 5). However, seed from certain species can be collected with fruits and stems intact and left in dry storage conditions for seed to mature (Delpratt & Gibson-Roy 2015).

Seed maturity indices include changes in color, fruit dehiscence, and seeds becoming hard and dry. It is highly recommended to clearly separate seed from fruits or coverings and to conduct cut test or pinch test before harvesting, to gauge fill, viability, and optimal timing of harvest as apparently “normal” fruits may be inviable. For many species, clarifying that the endosperm is firm and not soft is a key indication that seed is progressing towards maturity.

Small-Scale Seed Harvesting

Harvesting seed by hand is generally required to collect individual species within multispecies populations, those fruiting earlier or later than other species present in the same population, and at sites with difficult access or rugged terrain. Hand collection is used for seed collection from natural/managed populations and in cultivated production systems where crops are small, or species are of high value (e.g. seed price or species of conservation concern). Simple hand collection techniques include plucking, stripping, raking, clipping, or shaking seed from plants.

If seed dispersal/dehiscence occurs over longer periods seed can be captured using seed traps or bagging. Examples of such

are provided by Way and Gold (2014) and Cochrane et al. (2009). Ideally seed is taken directly from the plant rather than from the ground beneath where it may be old, moldy, infested with insects, at or near the point of germination, or from a different or nontarget species altogether. For seed retained at height, it is normally possible to bring seed to ground level using extendable pole pruners, catapults, or throw lines (with appropriate training and safeguards in place climbing may also be necessary) (Fig. 6). In all cases, ensure that proper safety and personal protective equipment is used (Kallow 2014).

Mechanical Seed Harvesting

In most cases, seed harvest from larger scale cultivated production systems is performed with mechanical equipment. Mechanical devices can range from small handheld equipment (e.g. vacuums or brush harvesters) (Fig. 6) through to large agricultural sized machines (Fig. 7). The choice of machine is typically dictated by a range of factors including type and spatial area of the crop, configuration of the crop bed, type of seed, and quantity of seed. A wide variety of agricultural and horticultural harvesters have been adapted for field-scale native seed harvest such as mini-combine harvesters, tractor-mounted brush harvesters, and vacuum harvesters.

Brush harvesters use rotating brushes (of different length, type, density) to displace seed/fruits from plants. Where unripened seed remains on plants further passes may be performed during one season to capture species with different maturation times (Adams et al. 2016) or new seed that is produced at a later stage. Vacuum harvesting—using handheld or vehicle-drawn

equipment—is a technique frequently employed for small, low-growing plants with diffuse, fine seed. This method is also effective for collecting seed directly from the ground (FloraBank 1999) especially where seed has fallen onto laid weed mat (ideally at or soon after dispersal to minimize the risk of seed loss through wind or from predation).

Brush and vacuum harvesters enable seed to be collected at different heights and times without damaging the plant. In contrast, harvesting equipment that cut stems, such as combine harvesters, may gather all seeds, regardless of their maturity state (noting that some species can mature post-harvest). If harvest options are limited to cutting methods, harvesting could be conducted on different parts of the crop at different times. Detailed species knowledge regarding timing of flowering and seed set will help growers to tailor harvest approaches and methods for species and production settings, thus ideally maximizing efficiency, yields, quality, and genetic diversity (Table 1).

Conclusions

Globally, vast quantities of seeds from a great diversity of plant species are critical for meeting large-scale restoration goals. Those species that exhibit the capacity for effective seed production (as managed natural populations or through cultivated seed production systems) and those with a specific need for increase (regardless of ease), such as rare or threatened species, should be candidates for investigation for these purposes so that effective and efficient ecological restoration can be conducted at-scale across the world. However, full ecological restoration based on the eight guiding principles in Gann et al. (2019) may ultimately require increasingly comprehensive suite of species be understood and integrated into seed production systems.

Native seed production is an emerging area across the world and significant research and adaptive management will be required to refine and enhance current methods and outcomes. Many standard agricultural and horticultural techniques have proven effective for use with a relatively narrow suite of wild species, but large information gaps remain for many others (Hancock et al. 2020). Nevertheless, cultivated seed production represents an area of unique potential for the supply of the most fundamental resource for ecological restoration—seed. To this end, managed natural populations and cultivated production systems provide an outstanding opportunity for delivering the quantity and quality of seed required for large-scale global restoration and every effort should be made to encourage and support their development.

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Supporting Information

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

Supplement S1. Seed collection

Supplement S2. Seed production

Supplement S3. Pollinators, pestand disease management

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