





STRATEGIC ISSUES ARTICLE

Seed use in the field: delivering seeds for restoration success

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Seed delivery to site is a critical step in seed-based restoration programs. Months or years of seed collection, conditioning, storage, and cultivation can be wasted if seeding operations are not carefully planned, well executed, and draw upon best available knowledge and experience. Although diverse restoration scenarios present different challenges and require different approaches, there are common elements that apply to most ecosystems and regions. A seeding plan sets the timeline and details all operations from site treatments through seed delivery and subsequent monitoring. The plan draws on site evaluation data (e.g. topography, hydrology, climate, soil types, weed pressure, reference site characteristics), the ecology and biology of the seed mix components (e.g. germination requirements, seed morphology) and seed quality information (e.g. seed purity, viability, and dormancy). Plan elements include: (1) Site treatments and seedbed preparation to remove undesirable vegetation, including sources in the soil seed bank; change hydrology and soil properties (e.g. stability, water holding capacity, nutrient status); and create favorable conditions for seed germination and establishment. (2) Seeding requirements to prepare seeds for sowing and determine appropriate seeding dates and rates. (3) Seed delivery techniques and equipment for precision seed delivery, including placement of seeds in germination-promotive microsites at the optimal season for germination and establishment. (4) A monitoring program and adaptive management to document initial emergence, seedling establishment, and plant community development and conduct additional sowing or adaptive management interventions, if warranted. (5) Communication of results to inform future seeding decisions and share knowledge for seed-based ecological restoration.

Key words: broadcast seeding, drill seeding, native seed, reference site, seed delivery, site preparation

Implications for Practice

- Site characteristics and the ecology and germination requirements of each species in the seed mix will guide development of the seeding plan that includes site preparation and seeding operations.
- Site preparation practices remove impediments to vegetation establishment and create a germination conducive soil seedbed.
- Seeding equipment and sowing strategies should be selected to provide optimal seed placement for each species in the seed mix. Good seed-to-soil contact is critical for successful seed germination and establishment.
- Monitoring seedling emergence and plant establishment in the first months and years post-seeding assesses seeding success and identifies needs for further treatments (e.g. weed control, seed addition). Continued long-term monitoring identifies the need for active management to ensure a satisfactory restoration trajectory is established.

and an integral part of the overall restoration plan created during the initial phases of a project (see Erickson & Halford 2020). A seeding plan (Fig. 1) includes data from the site evaluation,

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Introduction

A seeding plan that specifies when, where, and how native seed mixes will be used is the foundation for a successful field sowing

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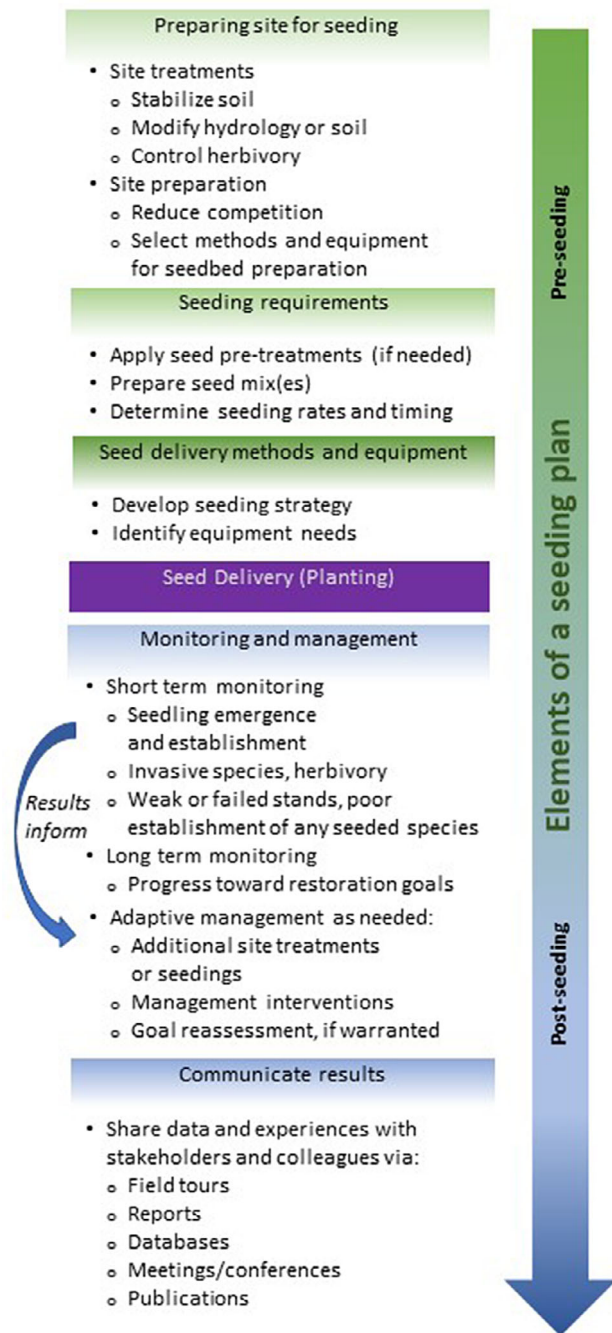


Figure 1 The suggested steps of a seeding plan from site treatments through communication of results.

including climate, hydrologic functioning, surface and slope stability, soil types and condition, native vegetation status, and problematic weed species (Krautzer et al. 2012; Armstrong et al. 2017). This is combined with information about the species to be sown and seed mix quality (Frischie et al. 2020) to provide a detailed timeline of actions required from site preparation through seeding and monitoring. The goal is to provide an

optimal germination environment for seeds of each species and establish seedlings at a desired density and species composition (Armstrong et al. 2017). Because hurdles (e.g. funding, resource limitations) or disruptive events (e.g. floods, drought, wildfires, herbivory) could occur, contingency and remediation plans should be considered. Common elements of most seeding plans include:

- (1) *Site treatments and seedbed preparation* to stabilize the site, remediate soil problems (e.g. compaction, nutrient levels, hydrological issues such as repellency, etc.), and resolve other problems identified by the site evaluation that might jeopardize seeding success and vegetation development. Operations are then conducted to remove competition, facilitate the seeding operation, and create an appropriate seedbed for the species being sown.
- (2) *Seeding requirements* include seed mix preparation and appropriate seeding dates and rates for each species in the mix. Seed pre-treatments to relieve dormancy or seed enhancement to facilitate seeding or improve germination and emergence may be required for some species.
- (3) *Seed delivery methods* are identified to efficiently and effectively deliver seeds of each species to appropriate microsites for establishment and growth. Equipment used in agriculture or forestry, implements developed for specific restoration situations, or manual methods can be selected.
- (4) *Monitoring and management* to assess initial emergence, seedling establishment, and plant community development and identify the need for additional seeding or adaptive management.
- (5) *Communicating results* locally and more broadly to inform future seed-based restoration projects.

Site Treatments and Seedbed Preparation

Site treatments prior to seeding may be required to remove or reduce competition with undesirable species, increase site stability, repair hydrologic function, or reduce nutrient levels (Morgan 2005). Seedbed preparation operations may then be required to produce physical disturbance of the germination substrate and provide establishment niches (Schmiede et al. 2012; Kiss et al. 2020). Tillage, herbicide application, prescribed fire, and other treatments can be used to create seedbed conditions appropriate to the species and seed delivery system (Whisenant 1999; Morgan 2005; Krautzer et al. 2012; Armstrong et al. 2017). These operations are essential for seedling establishment and vegetation development and can take months or even years to produce a soil condition suitable for optimizing germination and plant establishment. Such procedures should be identified early and incorporated in the seeding plan, budget, and scheduling process.

Mechanical Seedbed Preparation

Mechanical methods are frequently employed to prepare sites for seeding. Equipment can be selected to remove surface vegetation, reduce soil compaction, bury weed seeds, reduce erosion,



Figure 2 Mechanical seedbed preparation equipment: (A) Chisel plows are used for conservation tillage to control weeds, increase infiltration, and leave residue on the surface. (B) Mid-size offset disks till friable soils, turn under surface debris, break up surface crusts, and uproot shallow-rooted vegetation. (C) Pipe harrows with spiked pipes can be used on level to rocky and rugged terrain to reduce clods but leaves a rough surface. Photos: H. Wiedemann.

improve infiltration, break up surface crusts or clods, and firm the soil surface for seeding (Figs. 2, 3A & 3B). A number of reviews are available that describe the effectiveness of different plows, disks, harrows, and other implements for creating a suitable tilth for plant establishment (e.g. Munshower 1993; Whisenant 1999; Walker et al. 2004; Krautzer et al. 2012). In cases where the soil seed bank contains undesirable species or soils are fragile, tillage is not advised. Where surface and subsurface soil compaction are extreme, ripping with steel shanks can increase infiltration and improve soil conditions for seedling establishment. Most mechanized equipment, however, cannot be operated in wetlands, on rugged terrain, or in partially intact native plant communities. Alternative methods should be selected for such situations to protect site and operator safety.

Chemical Seedbed Preparation

Where removal of invasive species or existing undesirable vegetation is the primary concern, chemical treatments can be used alone or in combination with other methods. Chemical methods are often less costly than mechanical treatments, generally easily applied, and they can provide an adequate seedbed, reduce erosion potential, create a mulching effect, and be applied on rugged terrain (Whisenant 1999; Armstrong et al. 2017). Disadvantages of herbicide use in site preparation are human health and environmental concerns (impacts on waterways, soil health, and associated ecological processes), production of excessive litter (in some cases), and potential herbicide impacts on seeded species, residual natives, pollinators, and other organisms. Herbicide applicators must be appropriately trained, certified if required, and have access to personal protective equipment.

Other Site Preparation Methods

Topsoil replacement, fertilization, or inoculation may be necessary on some sites such as mine spoils or other severely degraded or soil-less sites to improve organic matter, nutrient status, and soil microbial communities (Munshower 1993). Conversely, on formerly cropped land, steps may be required to reduce nutrient status to favor native species and reduce weed invasions (Kirmer & Tischew 2014; Glenn et al. 2017). Techniques used to reduce nutrient status include soil inversion, deep tillage to mix topsoil with deeper soil layers, or cultivation without fertilization for one or more years. These techniques can also reduce the weed seedbank. Cover crops, nurse crops, or other transition plantings can also be established to improve site conditions and facilitate establishment of target species (Padilla & Pugnaire 2006; Kirmer et al. 2012).

Precision use of fire is employed in some circumstances to enhance natural regeneration in systems where such practices are well understood (Whisenant 1999; Campbell & Hooymans 2016). Planned burns can also be used to facilitate mechanical seedbed preparation and overseeding into existing vegetation (Ryan et al. 2013). However, great caution is required in the application of fire to ensure there is no unintended collateral damage, increased invasive species abundance, or loss of faunal species (Bradshaw et al. 2018).

Seeding Requirements

Seed and Seed Mix Preparation

Concerns when preparing native seed mixtures (Fig. 3) are the presence of seed units (fruits) with complex structures (e.g. florets, appendages) and the high variability in seed size and density that can cause uneven seed mixing and equipment



Figure 3 Seeding operations for converting degraded lands to forests and savannas in Brazil. (A) Seedbed preparation using a harrow. (B) Seedbed prepared with multiple harrow passes to break up clods and loosen the soil. (C, D) Seed mixes of tree, legume, and grass seeds with sand added to improve seed flow. (E) Direct seeding with a unit seeder in a nontillage system. (F) A broadcast spreader sowing native seed in tilled fields. (G) Seeds are hand broadcast in small or difficult to access areas. (H) Monitoring a broadcast seeding to assess biodiversity and development of cover. Photos kindly provided by Instituto Socioambiental, The Seed Path, and Agroicone, Brazil. Photos: (A) M. Ferreira, (B, C, D, F, G) N. Jacobi, (E) A. Canciano, (H) J. Prado.

blockages during seed delivery. Once the seeds required for a project are obtained (see Erickson & Halford 2020), each seed lot should be examined to determine whether further seed cleaning is required to improve seed flowability (Pedrini et al. 2018; Frischie et al. 2020). In addition, seed pre-treatments (e.g. scarification, application of chemical stimulants) may be required to relieve dormancy of some species (Kildisheva et al. 2020). Seed coatings (e.g. pelleting and encrusting) can further improve uniformity of seed size and shape and precision in seed metering and placement in the soil (Pedrini et al. 2020a). Seed coatings can also provide nutrients, inocula, or improved microsite conditions for sown seeds, particularly for seedings on arid lands or degraded soils such as found in post-mined areas.

Seed delivery method and seed and plant characteristics must be considered when creating the seed mix(es) (Erickson & Halford 2020). All species can be mixed together for sowing (Fig. 3), or they can be divided into separate mixes for seeding areas with different site conditions (e.g. soil type, hydrology). Separate seed boxes and seed drops (Fig. 4C) or operations can be used for small seeds that are surface seeded and pressed into the soil and larger seeds that are planted in the soil. Similarly, grasses and other more rapidly developing species can be segregated in separate rows or strips from slower growing forbs and woody species. Seeds that

are expensive or in short supply can be selectively seeded in areas most favorable for their establishment.

Seeding Rate

Seeding rates for individual species should be presented as the number or weight of pure live seeds (PLS) sown per area or row length. PLS is based on test results for seed lot purity, viability or germination, and 1,000 seed weight (see Armstrong et al. 2017; Erickson & Halford 2020; Frischie et al. 2020; Pedrini & Dixon 2020). In the absence of seed testing, bulk numbers of seed or bulk seed weight sown per area or row length is used (Goldblum et al. 2013). When mixtures of species are harvested together, the percentage of each species by weight following seed cleaning can be used to calculate approximate seeding rates.

Practitioner knowledge, results of previous restoration projects, and pertinent research outcomes can provide valuable guidance when setting seeding rates for the components of a mixture and the overall seeding rate. Survival percentages, however, are variable, and can be low, particularly on dry or highly disturbed sites (Whisenant 1999; Bainbridge 2007). Seeding rate guidelines are available for some plant communities and individual species (Diboll 2005; Kiehl et al. 2010; Kirmer et al. 2012; USDA NRCS 2019). Where these guidelines exist,



Figure 4 Seeding equipment: (A) Motorized seed mix delivery broadcaster for small-scale projects. This broadcaster provides some degree of seed-to-soil contact but requires a prepared seed bed (Romagnese, Italy). (B) Custom-made precision seeder for delivery of seed mixes used in reconstruction of farmland to the local reference community in southwestern Australia. (C) Minimum-till drills reduce surface disturbance. The triple seed box provides for separate seeding and even flow of large, small, and fluffy seeds. (D) Helicopters can seed irregular areas in rugged terrain and do not require a landing strip. Seed in the rotary spreader is dropped onto a spinner for distribution, but spread is affected by flight elevation, wind, and seed characteristics. (E) Hydroseeding a road cut in Oregon, U.S.A. Photos: (A) S. Pedrini, (C, E) U.S. Forest Service, (D) H. Wiedemann.

they serve as general recommendations and should be modified based on site evaluation, seed lot data, species growth habits, and specific project goals. Cost or availability of some native species can impact their seeding rate. Species richness can be improved in future years by natural dispersal to the restored site, overseeding, or planting seedlings, particularly species required at low densities such as tree species in woodland communities.

Timing of Seed Delivery

Seeding dates are determined by such factors as climate, seed ripening dates, and seed dormancy syndromes (Whisenant 1999; Frischie & Rowe 2011; Hardegee et al. 2016). Seed mixes may be applied on a single date or in sequential operations in subsequent years to mimic natural successional processes, where known. In general, seeding should be undertaken prior to the longest period of favorable growing conditions to maximize first-year growth, thereby enhancing survival and competitive ability with weedy species. Exposure of seeds to environmental conditions required to release dormancy and prepare seed for germination, however, may dictate different sowing dates for some species. For example, most tallgrass prairie species are sown in the autumn for the benefit of exposure to winter conditions that relieve dormancy and result in spring germination concurrent with natural emergence. However, early ripening tallgrass prairie species may require spring sowing and exposure to summer conditions to improve establishment (Frischie & Rowe 2011).

Seeding Depth

Recommendations for seeding depth vary by species and soil type (Whisenant 1999; Hardegee et al. 2016). Small seeds have limited energy reserves and often require exposure to light or specific day lengths as cues for germination (Kirmer et al. 2012). Such seeds should be sown on the soil surface and pressed onto the soil to provide good seed-to-soil contact without being buried too deeply. Small seeds are subject to drying and survival percentages may be low without such contact. Larger seeds with energy reserves sufficient for emergence can be sown at appropriate depths (based on natural emergence depths, if known) where moisture, temperature, nutrient, and microbial conditions may be more favorable (Bond et al. 1999). There is, however, a need for improved knowledge of optimal seeding depths for native species and development of seeding equipment that provides precise depth control (Masarei et al. 2019).

Seed Delivery

Selection of seeding methods and equipment requires consideration of equipment availability, the terrain, other site conditions, and the seed mix. Seeding methods and equipment are reviewed below.

Drill Seeding

Standard agricultural drills can be used to place seed in the soil on well-prepared sites with level terrain when soils are dry or

frozen (Fig. 3E). Rugged drills with high clearance are essential for use on rough or rocky terrain (Stevens & Monsen 2004). Minimum-till drills can be used to reduce surface disturbance (Fig. 4C). Drills can be fitted with multiple seed boxes (Fig. 4C) that segregate seeds of different sizes, morphological characteristics, competitive abilities, or growth habits and permit seeding them in separate rows and at different rates and depths, but careful calibration is required to avoid planting seed beyond their emergence capacity. Agitators maintain the seed flow in seed boxes for small seeds, while picker wheels move chaffy seed through seed boxes and reduce bridging in the seed drops (cross-meshing of seed that blocks delivery). Inert carriers (e.g. rice hulls, cracked wheat, vermiculite, clean sand) can be added to maintain seed mixing, improve seed flow, and facilitate seeding species with small or fluffy seeds. Press wheels, chains, imprinter wheels, or other mechanisms can be used to cover seeds in drill furrows or press seeds of surface-seeded species into the soil to increase seed-to-soil contact. To improve water availability in arid and semi-arid sites, deep furrow drills or equipment that creates divots, trenches, or other types of depressions can be used to enhance water catchment or trap snow (Bainbridge 2007).

Broadcast Seeding

Broadcast seeding places seed on the soil surface and is used in a variety of seeding scenarios, but it is often the most wasteful of all seed delivery methods. Broadcast seeding is conducted with equipment-mounted seed broadcasters, aerial broadcasting, or hand broadcasting (Fig. 4A–D) (Stevens & Monsen 2004). Precision in seed placement varies with the broadcasting equipment employed and the level of seedbed preparation. Where seed is broadcast on weed-prone or highly erodible sites or in areas where site preparation is otherwise inadequate or impossible, fewer seeds will land in appropriate microsites, and the resulting outcome will be inconsistent across the site. Higher seeding rates and, where feasible, use of a harrow (Figs. 2C, 3A & 3B), roller, rake, or other implement to improve seed-to-soil contact is recommended when broadcasting seed using equipment that does not provide for seed-to-soil contact (Turner et al. 2006).

Ground broadcasters mounted on tractors or utility vehicles are used to seed on level terrain when there is a well-prepared soil seedbed (Fig. 3F). Cultipackers and land imprinters create a pattern of depressions or pits to improve water catchment and can be used on moderate terrain where the soil is not rocky or highly compacted. Seed boxes or broadcasters can be attached to these implements to drop seed to the soil ahead of the implement, which then press it into the soil. Seed dribblers mounted in front of vehicle or tractor tires deliver seed in narrow strips that are pressed into the soil by the rolling tires. Dribblers are especially useful for adding diversity, including woody species, to depauperate natural vegetation or low-diversity seedings. Some ground broadcasters can be mounted on all-terrain vehicles and used in rugged areas that are not accessible to drill seeding equipment (Stevens & Monsen 2004; Campbell & Hooymans 2016).

Aerial broadcasting is used where large areas are to be seeded rapidly and on rugged or mountainous terrain that is not accessible to ground seeding equipment. Aerial broadcasting is accomplished with fixed-wing aircraft, helicopters (Fig. 4D), and, more recently, drones. Drones also have the capacity to map restoration areas to identify optimal microsites for seeding (Andrio 2018).

Hand broadcasting (Fig. 3G) is often the most efficient means of seeding small or fragmented areas with difficult access (e.g. understories, streambanks, wetlands, steep slopes), microsites within larger seedings that require specific seed mixes, or overseeding. Field crews and volunteers can distribute seed manually or with one of the many types of hand-held broadcasters available. However, depending on the ecosystem, species, and site conditions, outcomes can be highly variable.

Seed-Rich Hay Transfer

Transfer of seed-rich hay (Fig. 5) provides a means of capturing multiple species of local ecotypes to restore depleted native or near native grasslands and highly disturbed areas (Kiehl et al. 2010; Kirmer et al. 2012; Pedrini et al. 2020b). Green hay is harvested from appropriate donor sites (Fig. 5A–C) when most target species are mature and transported immediately to the receptor site where it is scattered by hand or with mechanical spreaders (Fig. 5D & 5E) (Kiehl et al. 2010; Scotton et al. 2012b). Hay can also be dried and stored until use. Threshing prior to

transport reduces volume and transport costs (Scotton & Ševčíková 2017). The hay also provides a mulch that improves micro-environmental conditions, conserves moisture, and reduces seed movement and erosion, though it can also limit seed-to-soil contact. Capturing seed of the full range of species and seed of different ripening stages of indeterminate species can require repeated harvests using a brush harvester or sequential harvests of different areas within the donor site (Pedrini et al. 2020b). Care must be taken to avoid overharvesting and species loss at the donor site (Meissen et al. 2017). Seed of additional local native species not present or not mature on the harvest date(s) can be sown on the restoration site before the hay is distributed or added to the threshed material prior to sowing (Kirmer & Tischew 2014; Baasch et al. 2016).

Hydroseeding

Hydroseeding (Fig. 4E) delivers seeds to sites that are inaccessible to ground seeding equipment or have a high risk of soil erosion (e.g. roadcuts, unstable or steep slopes) (Kirmer et al. 2012; Armstrong et al. 2017). Seed, mulch, fertilizers, soil additives, and an organic adhesive are mixed with water to form a thick slurry that is sprayed over the site with a high-pressure pump (Fig. 4E). Application equipment is mounted on trucks or tractors, but helicopters can be used in areas not accessible to vehicles. Hydromulching (an additional mulch layer applied and

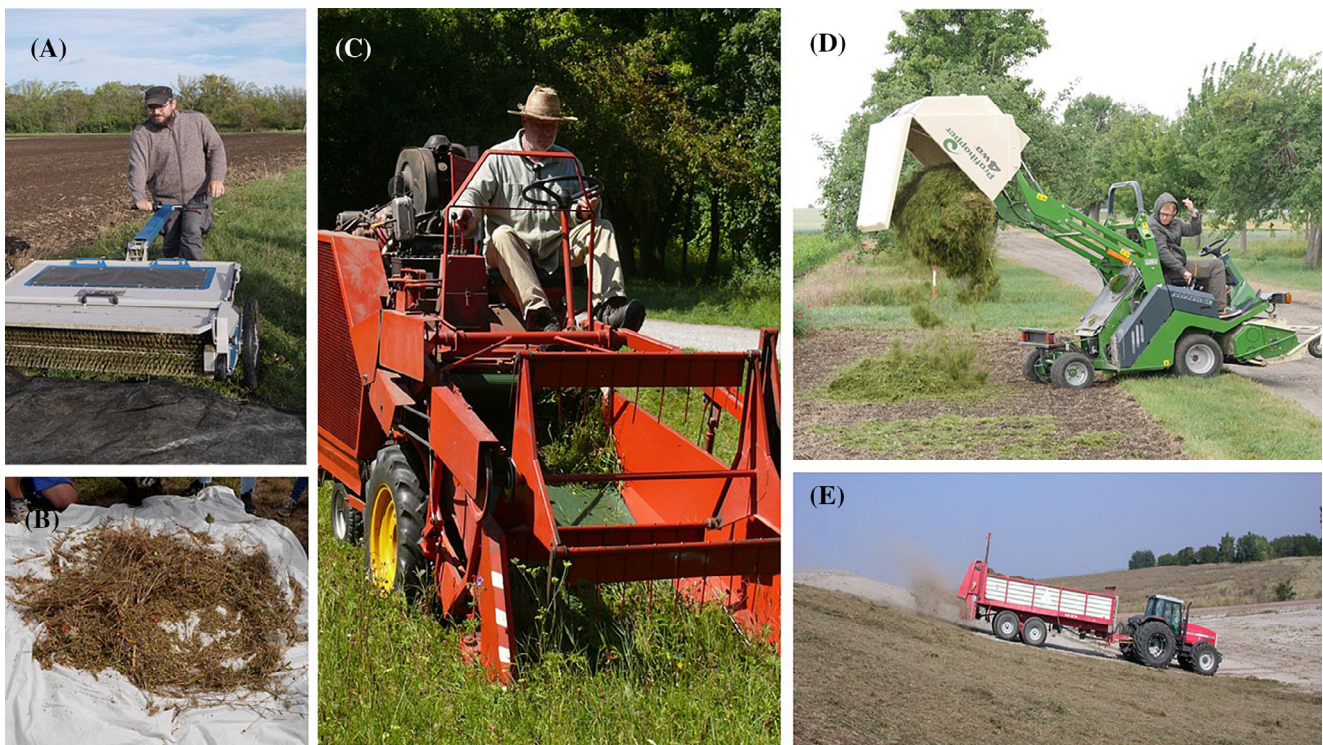


Figure 5 Seed-rich green hay harvested at a suitable donor site in Germany using equipment such as (A, B) a brush-type harvester that collects mature seeds and minimal vegetative material or (C) a plot harvester that produces threshed material. The seed-rich material should be transferred immediately to the receptor site and spread using equipment such as (D) a mower with a bucket spreader or (E) a manure spreader to restore species-rich near native grasslands and field margins. Photos: (A–D) A. Kirmer, (E) S. Mann.

fixed with an organic adhesive) can accelerate germination, protect seedlings from drying and frost, and provide protection against erosion caused by rain (Lee et al. 2018). It is important to spread the mulch evenly, prevent seed damage during application, ensure good seed-to-soil contact, and use appropriate fertilizer and mulch rates to minimize germination inhibition (Armstrong et al. 2017).

Mulching to Enhance Germination

Low or erratic moisture availability can preclude restoration success, especially in arid or seasonally arid landscapes. Organic mulch (e.g. hay, bark) is used in low-precipitation areas to enhance germination and emergence by retaining moisture and moderating the soil surface temperature (Ji & Unger 2001; Kader et al. 2019). Mulch depth and stability, light requirements for germination of seeded and weedy species, and species' responses to potential changes in soil C:N resulting from organic amendments are considerations when selecting mulch type and application depth (Fehmi & Kong 2012; Kirmer et al. 2012). Organic mulches may also reduce moisture availability by wicking moisture from the soil or intercepting moisture from light rains (Jalota & Prihar 1998).

Overseeding, Interseeding, and Gap Seeding

Overseeding, interseeding, and gap seeding involve the addition of seeds to enhance an existing natural community or seeding. These operations can be conducted to increase species diversity, alter community structure across a site, or restore depleted or weed-infested areas (Rayburn & Laca 2013; Silva et al. 2019). Diversification of species-poor native vegetation or seedlings is often hampered by microsite limitations (Münzbergová & Herben 2005); disturbance to reduce competition or improve microsite availability is often necessary before species introduction occurs (Schmiede et al. 2012; Baasch et al. 2016; Kiss et al. 2020).

Post-Seeding Monitoring and Management

Short- and long-term monitoring results provide a basis for assessing seeding success and informing future seeding plans. While monitoring can be time and resource intensive, post-seeding monitoring during the first few growing seasons of plant establishment and community development is critical (Scotton et al. 2012a). Sequential monitoring during this period can provide management information on: (1) problems encountered (e.g. weeds, herbivory) that require active management interventions; (2) a need for reseeded particular species or areas; (3) the percent of sown seed to emerge and establish; and (4) factors to consider in future seeding plans.

Protocols for monitoring and statistical analyses are available in many ecology books and regional manuals (e.g. Scotton et al. 2012a; U.S. Fish and Wildlife Service 2013). For seeding programs, measurements of species composition and abundance, and indices of relevant biodiversity measures (i.e. richness, evenness, etc.) are often used to describe restoration outcomes

(Fig. 3H). Additional biodiversity metrics, such as species diversity, reproductive maturity, and functional diversity, can help to determine ecosystem function and trajectory over the long term. Collaboration to include expertise on various taxonomic groups and aspects of community ecology (e.g. wildlife responses to the seeded plant community) can enhance monitoring program effectiveness and interpretation of results.

Communicating Results

Sharing monitoring data, and experiences gained with partners and stakeholders during meetings and field tours, provides an opportunity to acquire and share knowledge and increase support. Reporting results at conferences, through publicly available reports and publications, and via web reporting (such as providing the information for uploading to the International Network for Seed-based Restoration website) increases the availability of restoration outcomes to others working in similar plant communities or with similar seed-based restoration challenges and goals.

Conclusions

Improving the success of seed-based restoration requires effective site preparation, a sound understanding of plant and seed biology, and the use of site- and species-specific seed delivery methods. Today's seeding systems have evolved through innovative modifications of equipment and practices used in agriculture and forestry and novel approaches to meet the challenges of restoring specific disturbance types and improving diversity in highly varied ecosystems. Continued innovation and adaptation of equipment and technologies, extensive research on all aspects of site preparation and seed delivery, and inclusion of practitioner's knowledge are required to optimize existing systems for use with local resources. Careful short- and long-term monitoring is essential to identify and resolve problems, record successes, and contribute data to improve restoration approaches. Sharing outcomes, both positive and negative, is important for improving successful delivery of native seeds and for achieving ecological restoration targets.

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