Restoration Ecology
THE JOURNAL OF THE SOCIETY FOR ECOLOGICAL RESTORATION

INTRODUCTION ARTICLE

Setting the scene for dryland recovery: an overview and key findings from a workshop targeting seed-based restoration

Olga A. Kildisheva[1,2], Todd E. Erickson[1,3], David J. Merritt[1,3], Kingsley W. Dixon[1,3,4]

With nearly a quarter of global dryland systems considered to be degraded, the level and scale of degradation often exceed the thresholds for autogenic recovery, requiring human intervention to ensure that ecosystem biodiversity, structure, and function can be improved. A "Think Tank" workshop focusing on advancing the ecological approaches to large-scale restoration in degraded environments was held at Kings Park and Botanic Garden, Western Australia. Acknowledging that adaptive and broadly multidisciplinary strategies are paramount to achieving restoration in a repeatable and cost-effective manner, the workshop served as a forum to bring together plant scientists, ecologists, engineers, and environmental managers involved in dryland restoration from around the globe. This introductory paper to this special issue summarizes important contemporary challenges facing dryland restoration worldwide, offers a synthesis of the fundamental workshop themes, and provides a contextual overview for the series of invited papers in this issue, comprising reviews and case studies in seed and restoration technologies.

Key words: arid ecosystems, direct seeding, ecological function, ecosystem structure, large-scale ecological rehabilitation, native plant seed

Implications for Practice

- Global estimates of plant recruitment from seed are staggeringly low (90–95% average seed loss globally), with seed germination and emergence comprising the most critical phases in determining plant establishment success.
- Targeting key limitations to plant reestablishment associated with seed biology, edaphic, and environmental conditions, especially pertinent during the germination and establishment phases of plant development, can increase the efficiency and effectiveness of seed-based restoration.
- International collaboration and knowledge sharing are imperative to the development of adaptive, multidisciplinary strategies needed to ensure that restoration of dryland ecosystems can be achieved in a scalable, repeatable, and cost-effective manner.

Introduction to Drylands and Overview of the Special Issue

Drylands, which include arid, semiarid, and dry subhumid regions, account for nearly half of the global terrestrial surface area, support more than two billion people, store 45% of the global carbon, and represent a third of the biodiversity hotspots worldwide (Myers et al. 2000; Maestre et al. 2005; Reynolds et al. 2007; Verstraete et al. 2009; James et al. 2013). Extreme environmental limitations make these systems highly susceptible to degradation and significantly limit natural recovery following disturbance (Safriel et al. 2005; Bainbridge 2007; Reynolds et al. 2007). Land degradation, defined as the reduction of terrestrial productivity (Zika & Erb 2009), is estimated to affect up to 20% of global dryland systems (Safriel et al. 2005), and millions of hectares continue to be degraded each year (Brauch & Spring 2009). Shifts in ecosystem processes resulting from improper land management, the invasion of exotic species, and land alteration including high-impact resource extraction often push systems beyond the thresholds necessary for autogenic recovery, requiring human intervention to aid restoration (Bainbridge 2007; Carrick & Krüger 2007). The resulting losses of productivity and ecosystem function are estimated to cost US $42 billion annually (Brauch & Spring 2009) and threaten the biodiversity, as well as the socioeconomic and political sustainability, of arid systems (Stafford Smith & Reynolds 2002; Geist & Lambin 2004; Verstraete et al. 2009; Zika & Erb 2009; UNCCD 2012). To be effective, restoration tactics must match the current magnitude and rate of degradation by adopting

Author contributions: OAK conceived and completed the primary drafting of the manuscript; TEE, DJM, KWD conceived and edited the manuscript.

[1]School of Plant Biology, The University of Western Australia, Crawley, WA 6009, Australia
[2]Address correspondence to O. A. Kildisheva, email olga.kildisheva@research.uwa.edu.au
[3]Kings Park and Botanic Garden, Kings Park, WA 6005, Australia
[4]Department of Environment and Agriculture, Curtin University, Kent Street, Bentley, Perth, WA 6102, Australia

doi: 10.1111/rec.12392

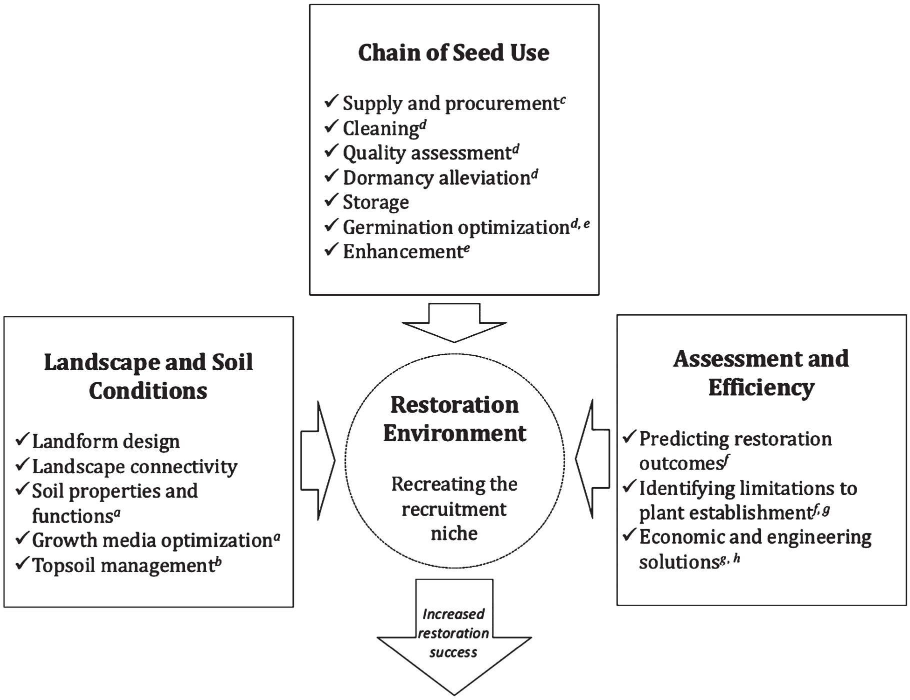

Figure 1. A conceptual framework highlighting topics addressed at the Restoration Seedbank Initiative's Think Tank Workshop focusing on "seed enablement technologies and recreating the recruitment niche in degraded environments" held in January, 2015, at Kings Park and Botanic Garden in Perth, Western Australia. This framework outlines the integration of research disciplines and restoration approaches that consider: (1) altered landscape and soil conditions, (2) factors relevant to seed and seedling establishment, as well as (3) techniques used to improve restoration effectiveness and efficiency through predictive and engineering solutions. The topics followed by a letter denote invited papers included in this special issue. [a]Muñoz-Rojas et al. (2016). [b]Golos et al. (2016). [c]Chivers et al. (2016). [d]Erickson et al. (2016*b*). [e]Madsen et al. (2016). [f]James and Carrick (2016). [g]Barrett-Lennard et al. (2016). [h]Guzzomi et al. (2016).

landscape-scale approaches that use science-driven technologies (Merritt & Dixon 2011; Suding 2011; Menz et al. 2013).

After many theoretical and empirical studies in restoration ecology (James et al. 2011, 2013), we are yet to fully realize and enact the technology and management changes that are needed to ensure restoration of dryland systems can achieve the required outcomes at any scale in a repeatable and cost-effective manner; solutions lie in development of adaptive, multidisciplinary strategies to tackle the challenges of restoration of this magnitude. Acknowledging this trend, a workshop was held on landscape-scale ecological restoration in January, 2015, at Kings Park and Botanic Garden, Western Australia, to bring together plant scientists, ecologists, engineers, and environmental managers involved in dryland restoration efforts around the world. The premise of the workshop was the ever-increasing pressure placed on natural ecosystems from human activities that create broad-scale land disturbance. These activities include pastoral, agricultural, and mining endeavors (among others), but the recent and unprecedented acceleration in mining activity in parts of Australia provided the catalyst for the workshop. Resource extraction has grown at a continuous rate across the globe, increasing by nearly a third from 1980 to 2002 (Behrens et al. 2007). Australia and North America exhibit the two highest rates of domestic extractive activities per capita, owing largely to metal ore, fossil fuel, minerals, and biomass harvesting (Behrens et al. 2007). A significant proportion of mining in these regions occurs in the arid and semiarid zones (BHP Billiton 2009; McKenzie et al. 2009). For example, in the arid Pilbara biogeographical region of northwest Australia—where more than 90% of Australia's iron ore is extracted (Ye 2008; Department of Mines and Petroleum 2015)—the current disturbance footprint exceeds 230,000 ha (Environmental Protection Authority 2014).

With this backdrop, the workshop aimed to address shortfalls in technologies that currently exist within restoration programs in dryland systems and to foster a multidisciplinary and global approach to understand these challenges and create practical solutions. Specific themes addressed during the workshop included: (1) landscape topography and modified soil substrates; (2) the development and implementation of the "chain of seed use" concept, and; (3) approaches for improving the efficiency of restoration practice and the assessment of restoration outcomes. Through a series of invited papers, this special issue of *Restoration Ecology* provides a synthesis of the core workshop themes including reviews and case studies in seed and restoration technologies (Fig. 1).

Landscape and Soil Conditions

Resource extraction often drastically alters the topography and physical properties of the landscape and impacts on natural ecosystems and biodiversity, mainly through the removal of the extant flora, fauna, and topsoil (Cooke & Johnson 2002). Soil functionality, defined here as the ability to support terrestrial ecosystem structure and function through physical, chemical, and biological processes (Brussaard 1997; Fitter et al. 2005), can be significantly diminished due to mining practices (i.e. stripping, improper storage, or mixing of the topsoil with the underlying substrate and mine rock burden) (Cooke & Johnson 2002; Golos 2013; Golos & Dixon 2014). Effective ecosystem recovery depends on the ability to accurately assess the degree of edaphic degradation.

The article by Muñoz-Rojas et al. (2016), *Soil quality indicators to assess functionality of restored soils in degraded semiarid ecosystems*, presents a novel and practical technique for assessing soil functionality and demonstrates its use in the context of post-mining restoration in the hot desert conditions of the Pilbara biogeographical region. The authors highlight the importance of considering the synergistic interplay between biotic and abiotic factors to understand the full scale of the reduction in soil functionality following disturbance, and demonstrate the role native vegetation communities can play in edaphic recovery.

Topsoil, which is often lost or diminished in the course of mineral extraction activities, is a significant source of seed, organic matter, nutrients, and microbes representative of the pre-mined conditions (Ghose 2001; Holmes 2001; da Silva et al. 2005; Carrick & Krüger 2007; Jasper 2007; Koch 2007; Rokich & Dixon 2007; Wick et al. 2009; Kiehl et al. 2010; Rivera et al. 2012). Many Australian mining operations have successfully conserved topsoil through strategic removal and storage prior to mining; however, the quality of topsoil can deteriorate during stockpiling and thus decline significantly in its potential to serve as a propagule source (Koch et al. 1996; Rokich & Dixon 2007; Rivera et al. 2012; Golos & Dixon 2014; Merritt et al. 2016). To understand the quantity and species composition of the residual topsoil seed bank, the article by Golos et al. (2016), *Plant recruitment from the soil seed bank depends on topsoil stockpile age, height, and storage history in an arid environment*, demonstrates the importance of topsoil in promoting autogenic vegetative recovery following mining and highlights the influence that topsoil management practices have on soil seed bank dynamics.

Chain of Seed Use

Seed-based restoration is the most widely used and spatially feasible approach to confront the expanding land disturbance footprint (Merritt & Dixon 2011) and much of the discussion of the workshop was focused on improving seed technologies for restoration. Current efforts aimed at restoring biodiversity and plant community function often rely on using large quantities of seed that must be collected from intact wild systems or procured from specialized producers (Broadhurst et al. 2008, 2015; Merritt & Dixon 2011).

For example, the U.S. Bureau of Land Management (BLM) is responsible for maintenance of over 160 million hectares of public lands and is the largest native seed consumer in the Western Hemisphere with major seed collection and curation programs (Haidet & Olwell 2015). In addition to wild seed collection, the BLM purchases over a thousand metric tonnes of seed per annum for restoration (Krabacher 2015) and spends up to $50 million USD ($67 million AUD) annually on seed procurement and seeding efforts (Knutson et al. 2009). Investments of a similar scale will need to be made in the coming decades by the mining industry in Australia; the seed purchases required to cover the estimated land disturbance footprint (e.g. >230,000 ha in the Pilbara; Environmental Protection Authority 2014) in just Western Australia, a single Australian state, are estimated to equate to well over $100 million AUD (circa $75 million USD) at current prices for wild-collected seed (Merritt & Dixon 2011).

In addition, limited or variable seed supply can significantly constrain the capacity of large-scale restoration efforts (Broadhurst et al. 2008, 2015; Gibson-Roy et al. 2010; Merritt & Dixon 2011, 2014; Tischew et al. 2011). For example, in the western United States, the inter-annual demand for native seed varies stochastically with the occurrence of catastrophic fires and is based, spatially, on the geographic distribution of fire incidence. As a result, seed producers often cannot accurately predict species demand, while wild-land seed collection programs do not have the capacity to provide adequate seed quantities. At the landscape scale, the consequence of these factors is often an inability to source adequate quantities of seeds or sufficient diversity of species to meet basic biodiversity and genetic provenance standards. Even with adequate foresight to predict the timing and size of the disturbance footprint, such as in the case of mining operations, obtaining seed of desired species in the quantities required can be difficult (Lippitt et al. 1994; Mortlock 2000; Merritt & Dixon 2011, 2014; Tischew et al. 2011; Broadhurst et al. 2015).

In order to ensure sufficient seed availability, seed farming, or the increase of native species through agricultural-style production systems, is an area in need of significant development (Merritt & Dixon 2011; Tischew et al. 2011). In an article included in this issue by Chivers et al. (2016), *The merits of artificial selection for the development of restoration-ready plant materials of native perennial grasses*, the authors highlight the role seed farming of native grasses can play in restoration of arid systems, emphasizing how effective and efficient production systems can lead to material increases in seed availability with concomitant reduction in seed costs. Citing examples from the United States and Australia, the article highlights the potential of artificial selection to enhance vegetative performance to overcome the most limiting restoration site factors, but emphasizes the importance of using caution to avoid unfavorable (and possibly unexpected) outcomes to biodiversity conservation (i.e. inbreeding depression and the loss of potentially useful traits).

Given the limited quantity and high cost associated with native seed procurement, it is imperative that restoration practitioners use seed resources wisely and efficiently to minimize waste (Merritt & Dixon 2011). Currently, seed-based plant recovery is hampered by low or unpredictable establishment rates. Figures from around the globe demonstrate that only

5–10% of seeds delivered to restoration sites result in an established seedling (Williams et al. 2002; Turner et al. 2006*a*; Merritt & Dixon 2011; Sheley et al. 2011; Wagner et al. 2011; Hardegree et al. 2013). Aside from losses due to seed predation (Hulme 1996; Holl 1999; Bricker et al. 2010; Woodall 2010; Tsegaye et al. 2011), much of the failure to meet establishment outcomes can be attributed to the lack of biological and technical knowledge associated with seed germination biology (Merritt et al. 2007; Erickson et al. 2016*a*). On average, more than 80% of dryland floras produce seeds that exhibit some level dormancy (Baskin & Baskin 2014) that if not understood and appropriately managed may lead to plant establishment failure.

Identifying the specific mechanisms of seed dormancy at play for a particular species allows the development of techniques to alleviate this dormancy prior to sowing, that in turn can considerably enhance germination (Turner et al. 2013). Techniques for dormancy alleviation vary based on the kind of dormancy present, but all aim to enhance the germination capacity of a seed population and, where possible, fast-track dormancy loss in a reliable and repeatable manner (Baskin & Baskin 2014). Some examples include the use of mechanical or chemical abrasion, wet or dry heat, dry after-ripening, warm and cold stratification, and the use of chemical stimulants (e.g. gibberellic acid, karrikinolide, and ethylene) (Hargurdeep et al. 1986; Morris 2000; Bonner & Karrfalt 2008; Commander et al. 2009*a*, 2009*b*; Turner et al. 2009; Kildisheva et al. 2011; Baskin & Baskin 2014; Erickson et al. 2016*a*). A number of dormancy alleviation techniques have been successfully applied in the context of large-scale restoration (Rokich et al. 2002; Rokich & Dixon 2007; Erickson et al. 2016*a*). The second article in this section by Erickson et al. (2016*b*), *Overcoming physiological dormancy in seeds of* Triodia *(Poaceae) to improve restoration in the arid zone*, focuses on the alleviation of physiological dormancy; the most common type of dormancy among global dryland systems (Baskin & Baskin 2004 2014; Kos et al. 2012). In this article, the authors demonstrate how the replication of the temperature and moisture conditions typical of the soil seed bank (through dry after-ripening) combined with the use of chemical growth stimulants (i.e. gibberellic acid and karrikinolide) can effectively improve seed germination performance of a suite of grass species. The authors present examples of how these techniques can be easily implemented within restoration programs to enhance the recovery of a dominant genus endemic to the arid and semiarid regions of inland Australia.

Suboptimal climatic and edaphic conditions, combined with biotic pressures, can further challenge plant community establishment in dryland systems because, relative to the tolerance of adult plants, plant microclimatic requirements are much more restrictive during the germination, emergence, and establishment phases (Call & Roundy 1991; Peters 2000; Hardegree et al. 2003; James et al. 2011). The use of seed enhancement technologies may assist in overcoming a variety of constraints to plant recruitment. Seed enhancement technologies, defined as any post-harvest methods used to improve germination, increase seedling growth, reduce predation, and facilitate planting, have been used in the horticulture, turf, and agriculture industries for decades (Taylor & Harman 1990; Taylor et al. 1998; Chun et al. 2006; Halmer 2008; Bewley et al. 2011) but have only recently gained traction in restoration ecology (Turner et al. 2006*b*; Madsen et al. 2012*a*, 2012*b*, 2012*c*, 2012*d*, 2013, 2014; Abella et al. 2015; Perring et al. 2015; Merritt et al. 2016). Technologies for seed enhancement can be designed to address site-, species-, and time-specific bottlenecks to seed germination and plant establishment. Madsen et al. (2016) in their contribution to this special issue, *Emerging seed enhancement technologies for overcoming barriers to restoration*, examine the key limitations to seed-based restoration and outline innovative seed enhancement strategies designed to overcome these limitations in the sagebrush (*Artemisia* L. spp.) steppe ecosystems of western North America.

Assessment and Efficiency

Positive restoration outcomes depend on the ability of land management practitioners to integrate scientific knowledge into a functional and efficient restoration process. Given the scale and rate of ecosystem disturbance globally, the capacity to scale up is integral to achieving restoration goals at a landscape scale. Dryland degradation is likely to expand substantially as a result of global climate change and population growth (Reynolds et al. 2007). Costs associated with restoration increase exponentially with the intensity of degradation, whereas the capacity to enact successful restoration decreases with the degree of socioeconomic limitation and institutional inaction (Acheson 2006; Mangora 2011; James et al. 2013; Menz et al. 2013). Restoration capacity can therefore be defined by the relationship between restoration cost and the likelihood of success. In other words, at the same level of resource availability, more cost-effective practices will result in greater restoration capacity (James et al. 2013). Thus, the ability to predict ecological restoration outcomes based on the cause of disturbance and the means of intervention holds significant merit. James and Carrick (2016) in their contribution to this special issue, *Towards quantitative dryland restoration models*, present a "systems approach model," which is a quantitative, process-based method designed to predict restoration outcomes under different disturbance levels and management scenarios. This approach can serve as a framework for adaptive restoration management and influence the decision-making process through identifying key limitations to plant establishment, helping to assess potential solutions, and evaluating costs.

The understanding of key microclimate limitations to plant establishment following large-scale disturbance can aid in reconstructing suitable conditions to promote vegetative recovery. In their paper included in this issue, *Improving saltland revegetation through understanding the "recruitment niche": potential lessons for ecological restoration in extreme environments*, Barrett-Lennard et al. (2016) used a multidecade study of salt-land rehabilitation to illustrate how regeneration bottlenecks can be overcome using a variety of microsite modifications to contribute to improved plant establishment and return economic value to degraded landscapes.

The mechanization and streamlining of seed production, handling, and treatment techniques to produce "restoration ready" seeds combined with the use of machinery designed for soil stabilization, microsite modification, and precision seeding may present additional benefits to restoration efficiency and long-term cost savings. In their article, *Flash flaming effectively removes appendages and improves the seed coating potential of grass florets*, Guzzomi et al. (2016) highlight the benefits of inter-disciplinary collaboration through applying an engineering solution to improve seed handling and simplify the application of seed enhancement technologies.

Concluding Remarks

The recognition of the role that dryland regions play in supporting human and biological systems is disproportionately limited, relative to other ecosystems (Safriel et al. 2005; Reynolds et al. 2007). Issues of ecological degradation in these biomes have traditionally received little exposure due to the historic absence of focused international science programs—often compounded by their regional isolation. However, partially as a result of revenue from resource extraction, many dryland regions have gained the financial capacity to support and develop research-driven restoration programs, albeit those that are focused on comparatively small disturbance footprints. Recent collaborative advances in various disciplines that contribute to restoration ecology (relevant to drylands), combined with the recognition of their importance by industry, government, and the private sector, have resulted in substantial cross-continental collaboration and knowledge sharing. The concepts and data captured in this special issue of *Restoration Ecology* serve as an example of what can result from an international, multidisciplinary approach to ecological restoration, and provide impetus for the formation of a common framework for managing dryland systems. It is our hope that by combining scientific understanding and practical experience we can help shape policy and practice in order to improve restoration effectiveness on a global scale.

Acknowledgments

This article is a direct outcome of discussions held during the Restoration Seedbank Initiative's Think Tank Workshop focusing on "seed enablement technologies and recreating the recruitment niche in degraded environments." Logistical and financial support was provided by a BHP Billiton Iron Ore Community Development Project (contract no. 8600048550) under the auspices of the Restoration Seedbank Initiative, a partnership between BHP Billiton Iron Ore, The University of Western Australia, and the Botanic Gardens and Parks Authority. All authors acknowledge that there is no conflict of interest.

LITERATURE CITED

Abella SR, Chiquoine LP, Engel EC, Kleinick KE, Edwards FS (2015) Enhancing quality of desert tortoise habitat: augmenting native forage and cover plants. Journal of Fish and Wildlife Management 6:278–289

Acheson JM (2006) Institutional failure in resource management. Annual Review of Anthropology 35:117–134

Bainbridge DA (2007) A guide for desert and dryland restoration. Island Press, Washington D.C.

Barrett-Lennard EG, Norman HC, Dixon KW (2016) Improving saltland revegetation through understanding the 'recruitment niche': potential lessons for ecological restoration in extreme environments. Restoration Ecology 24: S91–S97

Baskin JM, Baskin CC (2004) A classification system for seed dormancy. Seed Science Research 14:1–16

Baskin CC, Baskin JM (2014) Seeds: ecology, biogeography, and evolution of dormancy and germination. 2nd edition. Academic Press, San Diego, California

Behrens A, Giljum S, Kovanda J, Niza S (2007) The material basis of the global economy. Ecological Economics 64:444–453

Bewley JD, Black M, Halmer P (2011) The encyclopedia of seeds science, technology and uses. CABI, Wallingford, United Kingdom

BHP Billiton (2009) Appendix T. Rehabilitation and closure. Olympic dam expansion draft environmental impact statement. http://www.bhpbilliton.com/society/regulatory (accessed 21 Jan 2016)

Bonner FT, Karrfalt RP (2008) The woody plant seed manual. U.S. Department of Agriculture, Forest Service, Washington D.C., http://www.treesearch.fs.fed.us/pubs/32626 (accessed 21 Jan 2016)

Brauch HG, Spring UO (2009) Securitizing the Ground Grounding Security Secretariat of the United Nations Convention to Combat Desertification. Issue paper no 2. UNCCD, Bonn, Germany

Bricker M, Pearson D, Maron J (2010) Small-mammal seed predation limits the recruitment and abundance of two perennial grassland forbs. Ecology 9:85–92

Broadhurst LM, Lowe A, Coates DJ, Cunningham SA, McDonald M, Vesk PA, Yates C (2008) Seed supply for broadscale restoration: maximizing evolutionary potential. Evolutionary Applications 1:587–597

Broadhurst L, Driver M, Guja L, North T, Vanzella B, Fifield G, Bruce S, Taylor D, Bush D (2015) Seeding the future—the issues of supply and demand in restoration in Australia. Ecological Management & Restoration 16:29–32

Brussaard L (1997) Biodiversity and ecosystem functioning in soil. Ambio 26:563–570

Call CA, Roundy BA (1991) Perspectives and processes in revegetation of arid and semiarid rangelands. Journal of Range Management 44:543–549

Carrick PJ, Krüger R (2007) Restoring degraded landscapes in lowland Namaqualand: lessons from the mining experience and from regional ecological dynamics. Journal of Arid Environments 70:767–781

Chivers IH, Jones TA, Broadhurst LM, Mott IW, Larson SR (2016) The merits of artificial selection for the development of restoration-ready plant materials of native perennial grasses. Restoration Ecology 24:174–183 [intended for this issue though inadvertedly published in REC 24:2]

Chun C, Sanders DC, Yi C, Leskovar DI (2006) Proceedings of the International Symposium on Seed Enhancement and Seedling Production Technology: Seoul, Korea, August 13–19, 2006. 27th International Horticulture Congress and Exhibition. International Society for Horticultural Science, Leuven, Belgium

Commander LE, Merritt DJ, Rokich DP, Dixon KW (2009*a*) The role of after-ripening in promoting germination of arid zone seeds: a study on six Australian species. Botanical Journal of the Linnean Society 161:411–421

Commander LE, Merritt DJ, Rokich DP, Dixon KW (2009*b*) Seed biology of Australian arid zone species: germination of 18 species used for rehabilitation. Journal of Arid Environments 73:617–625

Cooke JA, Johnson MS (2002) Ecological restoration of land with particular reference to the mining of metals and industrial minerals: a review of theory and practice. Environmental Reviews 10:41–71

Department of Mines and Petroleum (2015) Latest statistics release. http://www.dmp.wa.gov.au/1525.aspx (accessed 1 Nov 2015)

Environmental Protection Authority (2014) Cumulative environmental impacts of development in the Pilbara region: advice of the Environmental Protection Authority to the Minister for Environment under Section 16(e) of the Environment Protection Act 1986. Government of Western Australia, Perth, Australia

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

Erickson TE, Shackelford N, Dixon KW, Turner SR, Merritt DJ (2016b) Overcoming physiological dormancy in seeds of *Triodia* (Poaceae) to improve restoration in the arid zone. Restoration Ecology 24:S64–S76

Fitter AH, Gilligan CA, Hollingworth K, Kleczkowski A, Twyman RM, Pitchford JW (2005) Biodiversity and ecosystem function in soil. Functional Ecology 19:369–377

Geist HJ, Lambin EF (2004) Dynamic causal patterns of desertification. Bioscience 54:817

Ghose M (2001) Management of topsoil for geo-environmental reclamation of coal mining areas. Environmental Geology 40:1405–1410

Gibson-Roy P, Moore G, Delpratt J, Gardner J (2010) Expanding horizons for herbaceous ecosystem restoration: the Grassy Groundcover Restoration Project. Ecological Management and Restoration 11:176–186

Golos PJ (2013) Restoring vegetation on waste rock dumps at the Telfer mine site in Australia's Great Sandy Desert: topsoil management and plant establishment. Doctoral thesis. University of Western Australia, Perth, Australia

Golos PJ, Dixon KW (2014) Waterproofing topsoil stockpiles minimizes viability decline in the soil seed bank in an arid environment. Restoration Ecology 22:495–501

Golos PJ, Dixon KW, Erickson TE (2016) Plant recruitment from the soil seed bank depends on topsoil stockpile age, height, and storage history in an arid environment. Restoration Ecology 24:S53–S61

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

Haidet M, Olwell P (2015) Seeds of success: a national seed banking program working to achieve long-term conservation goals. Natural Areas Journal 35:165–173

Halmer P (2008) Seed technology and seed enhancement. Acta Horticulturae 771:17–26

Hardegree SP, Flerchinger GN, Van Vactor SS (2003) Hydrothermal germination response and the development of probabilistic germination profiles. Ecological Modelling 167:305–322

Hardegree SP, Moffet CA, Flerchinger GN, Cho J, Roundy BA, Jones TA, James JJ, Clark PE, Pierson FB (2013) Hydrothermal assessment of temporal variability in seedbed microclimate. Rangeland Ecology and Management 66:127–135

Hargurdeep SS, Bassi PK, Spencer MS (1986) Use of ethylene and nitrate to break seed dormancy of common lambsquarters (*Chenopodium album*). Weed Science 34:502–506

Holl KD (1999) Factors limiting tropical rain forest regeneration in abandoned pasture: seed rain, seed germination, microclimate, and soil. Biotropica 31:229–242

Holmes PM (2001) Shrubland restoration following woody alien invasion and mining: effects of topsoil depth, seed source, and fertilizer addition. Restoration Ecology 9:71

Hulme PE (1996) Natural regeneration of yew (*Taxus baccata* L.): microsite, seed or herbivore? Journal of Ecology 84:853–861

James JJ, Carrick PJ (2016) Towards quantitative dryland restoration models. Restoration Ecology 24:S85–S90

James JJ, Svejcar TJ, Rinella MJ (2011) Demographic processes limiting seedling recruitment in arid grassland restoration. Journal of Applied Ecology 48:961–969

James JJ, Sheley RL, Erickson T, Rollins KS, Taylor MH, Dixon KW (2013) A systems approach to restoring degraded drylands. Journal of Applied Ecology 50:730–739

Jasper DA (2007) Beneficial soil microorganisms of the jarrah forest and their recovery in bauxite mine restoration in Southwestern Australia. Restoration Ecology 15:S74–S84

Kiehl K, Kirmer A, Donath TW, Rasran L, Hölzel N (2010) Species introduction in restoration projects—evaluation of different techniques for the establishment of semi-natural grasslands in Central and Northwestern Europe. Basic and Applied Ecology 11:285–299

Kildisheva OA, Dumroese RK, Davis AS (2011) Overcoming dormancy and enhancing germination of *Sphaeralcea munroana* seeds. HortScience 46:1672–1676

Knutson KC, Pyke DA, Wirth TA, Pilliod DS, Brooks ML, Chambers JC (2009) A chronosequence feasibility assessment of emergency fire rehabilitation records within the Intermountain Western United States. Final report to the Joint Fire Science Program, project no. 08-S-08. U.S. Geological Survey, Reston, Virginia

Koch JM (2007) Alcoa's mining and restoration process in south Western Australia. Restoration Ecology 15:S11–S16

Koch JM, Ward SC, Grant CD, Ainsworth GL (1996) Effects of bauxite mine restoration operations on topsoil seed reserves in the jarrah forest of Western Australia. Restoration Ecology 4:368–376

Kos M, Baskin CC, Baskin JM (2012) Relationship of kinds of seed dormancy with habitat and life history in the Southern Kalahari flora. Journal of Vegetation Science 23:869–879

Krabacher P (2015) Procurement and application of native plant material in the BLM. The right seed in the right place at the right time: tools for sustainable restoration. January–May 2015 Webinar Series. http://www.greatbasinnpp.org/2015-webinar-seed-collection (accessed 21 Jan 2016)

Lippitt L, Fidelibus MW, Bainbridge DA (1994) Native seed collection, processing, and storage for revegetation projects in the western United States. Restoration Ecology 2:120–131

Madsen MD, Davies KW, Williams CJ, Svejcar TJ (2012*a*) Agglomerating seeds to enhance native seedling emergence and growth. Journal of Applied Ecology 49:431–438

Madsen MD, Kostka SJ, Inouye AL, Zvirzdin DL (2012*b*) Postfire restoration of soil hydrology and wildland vegetation using surfactant seed coating technology. Rangeland Ecology & Management 65:253–259

Madsen MD, Petersen SL, Fernelius KJ, Roundy BA, Taylor AG, Hopkins BG (2012*c*) Influence of soil water repellency on seedling emergence and plant survival in a burned semi-arid woodland. Arid Land Research and Management 26:236–249

Madsen MD, Petersen SL, Roundy BA, Hopkins BG, Taylor AG (2012*d*) Comparison of postfire soil water repellency amelioration strategies on bluebunch wheatgrass and cheatgrass survival. Rangeland Ecology & Management 65:182–188

Madsen MD, Davies KW, Boyd CS, Kerby JD, Carter DL, Svejcar TJ (2013) Restoring North America' s sagebrush steppe ecosystem using seed enhancement technologies. Pages 393–401. In: Michalk DL, Millar GD, Badgery WB, Broadfoot KM (eds) Proceedings of the 22nd International Grassland Congress: revitalising grasslands to sustain our communities. New South Wales Department of Primary Industry, Orange, Australia

Madsen MD, Davies KW, Mummey DL, Svejcar TJ (2014) Improving restoration of exotic annual grass-invaded rangelands through activated carbon seed enhancement technologies. Rangeland Ecology & Management 67:61–67

Madsen MD, Davies KW, Boyd CS, Kerby JD, Svejcar TJ (2016) Emerging seed enhancement technologies for overcoming barriers to restoration. Restoration Ecology 24:S77–S84

Maestre FT, Valladares F, Reynolds JF (2005) Is the change of plant–plant interactions with abiotic stress predictable? A meta-analysis of field results in arid environments. Journal of Ecology 93:748–757

Mangora MM (2011) Poverty and institutional management stand-off: a restoration and conservation dilemma for mangrove forests of Tanzania. Wetlands Ecology and Management 19:533–543

McKenzie N, van Leeuwen S, Pinder A (2009) Introduction to the Pilbara biodiversity survey, 2002–2007. Records of the Western Australian Museum 78(supplement):3–89

Menz MHM, Dixon KW, Hobbs RJ (2013) Hurdles and opportunities for landscape-scale restoration. Science 339:526–527

Merritt DJ, Dixon KW (2011) Restoration seed banks—a matter of scale. Science 332:424–425

Merritt DJ, Dixon KD (2014) Seed availability for restoration. Pages 97–104. In: Bozzano M, Jalonen R, Thomas E, Boshier D, Gallo L, Cavers S, Bordács S, Smith P, Loo J (eds) Genetic considerations in ecosystem restoration using native tree species. State of the world's forest genetic resources—thematic study. FAO and Biodiversity International, Rome, Italy

Merritt DJ, Turner SR, Clarke S, Dixon KW (2007) Seed dormancy and germination stimulation syndromes for Australian temperate species. Australian Journal of Botany 55:336–344

Merritt DJ, Golos PJ, Erickson TE (2016) A systematic approach to seed management for restoration. Pages 35–42. In: Erickson TE, Barrett RL, Merritt DJ, Dixon KW (eds) Pilbara seed atlas and field guide: plant restoration in Australia's arid northwest. CSIRO Publishing, Dickson, Australia

Morris EC (2000) Germination response of seven east Australian *Grevillea* species (Proteaceae) to smoke, heat exposure and scarification. Australian Journal of Botany 48:179–189

Mortlock W (2000) Local seed for revegetation. Ecological Management & Restoration 1:93–101

Muñoz-Rojas M, Erickson TE, Dixon KW, Merritt DJ (2016) Soil quality indicators to assess functionality of restored soils in degraded semi-arid ecosystems. Restoration Ecology 24:S43–S52

Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GA, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403:853–858

Perring MP, Standish RJ, Price JN, Craig MD, Erickson TE, Ruthrof KX, Whiteley AS, Valentine LE, Hobbs RJ (2015) Advances in restoration ecology: rising to the challenges of the coming decades. Ecosphere 6:1–25

Peters DPC (2000) Climatic variation and simulated patterns in seedling establishment of two dominant grasses at a semi-arid-arid grassland ecotone. Journal of Vegetation Science 11:493–504

Reynolds JF, Smith DMS, Lambin EF, Turner BL, Mortimore M, Batterbury SPJ, et al. (2007) Global desertification: building a science for dryland development. Science 316:847–851

Rivera D, Jáuregui BM, Peco B (2012) The fate of herbaceous seeds during topsoil stockpiling: restoration potential of seed banks. Ecological Engineering 44:94–101

Rokich DP, Dixon KW (2007) Recent advances in restoration ecology, with a focus on the Banksia woodland and the smoke germination tool. Australian Journal of Botany 55:375–389

Rokich DP, Dixon KW, Sivasithamparam K, Meney KA (2002) Smoke, mulch, and seed broadcasting effects on woodland restoration in Western Australia. Restoration Ecology 10:185–194

Safriel U, Adeel Z, Niemeijer D, Puigdefabregas J, White R, Lal R, et al. (2005) Dryland systems. Pages 623–662. In: Hassan R, Scholes R, Ash N (eds) Ecosystems and human well-being: current state and trends: findings of the condition and trends working group. Island Press, Washington D.C.

Sheley RL, James J, Rinella MJ, Blumenthal DM, DiTomasso JM (2011) A scientific assessment of invasive plant management on anticipated conservation benefits. Pages 291–335. In: Briske DD (ed) Conservation benefits of rangeland practices: assessment, recommendations, and knowledge gaps. Allen Press, Lawrence, Kansas

da Silva GA, Trufem SFB, Saggin Júnior OJ, Maia LC (2005) Arbuscular mycorrhizal fungi in a semiarid copper mining area in Brazil. Mycorrhiza 15:47–53

Stafford Smith DM, Reynolds JF (2002) Desertification: a new paradigm for an old problem. Pages 403–424. In: Reynolds JF, Stafford Smith DM (eds) Global desertification: do humans cause deserts? Dahlem University Press, Berlin, Germany

Suding KN (2011) Toward an era of restoration in ecology: successes, failures, and opportunities ahead. Annual Review of Ecology, Evolution, and Systematics 42:465–487

Taylor AG, Harman GE (1990) Concepts and technologies of selected seed treatments. Annual Review of Phytopathology 28:321–339

Taylor G, Allen PS, Bennett M, Bradford KJ, Burris JS, Misra MK (1998) Seed enhancements. Seed Science Research 8:245–256

Tischew S, Youtie B, Kirmer A, Shaw N (2011) Farming for restoration: building bridges for native seeds. Ecological Restoration 29:219–222

Tsegaye D, Moe SR, Haile M (2011) Seed predation and moisture limit germination of recalcitrant *Dobera glabra* (Salvadoraceae) seeds in the Afar rangelands, Ethiopia. Journal of Arid Environments 75:903–908

Turner SR, Merritt DJ, Baskin JM, Baskin CC, Dixon KW (2006a) Combinational dormancy in seeds of the Western Australian endemic species *Diplopeltis huegelii* (Sapindaceae). Australian Journal of Botany 54:565–570

Turner SR, Pearce B, Rokich DP, Dunn RR, Merritt DJ, Majer JD, Dixon KW (2006b) Influence of polymer seed coatings, soil raking, and time of sowing on seedling performance in post-mining restoration. Restoration Ecology 14:267–277

Turner SR, Merritt DJ, Renton MS, Dixon KW (2009) Seed moisture content affects afterripening and smoke responsiveness in three sympatric Australian native species from fire-prone environments. Austral Ecology 34:866–877

Turner SR, Steadman KJ, Vlahos S, Koch JM, Dixon KW (2013) Seed treatment optimizes benefits of seed bank storage for restoration-ready seeds: the feasibility of prestorage dormancy alleviation for mine-site revegetation. Restoration Ecology 21:186–192

UNCCD (2012) Zero net land degradation: a sustainable development goal for Rio+20 UNCCD secretariat recommendations for policy-makers. United Nations Convention to Combat Desertification, Bonn, Germany

Verstraete MM, Scholes RJ, Smith MS (2009) Climate and desertification: looking at an old problem through new lenses. Frontiers in Ecology and the Environment 7:421–428

Wagner M, Pywell RF, Knopp T, Bullock JM, Heard MS (2011) The germination niches of grassland species targeted for restoration: effects of seed pre-treatments. Seed Science Research 21:117–131

Wick AF, Stahl PD, Ingram LJ, Vicklund L (2009) Soil aggregation and organic carbon in short-term stockpiles. Soil Use and Management 25:311–319

Williams MI, Schuman GE, Hild AL, Vicklund LE (2002) Wyoming big sagebrush density: effects of seeding rates and grass competition. Restoration Ecology 10:385–391

Woodall GS (2010) Improving the direct sowing of commercial native plants in agricultural lands of southern Australia. Rural Industries Research and Development Corporation (RIRDC) Publication no.10-061, Australian Government, Canberra, Australia. http://rirdc.infoservices.com.au/items/10-061 (accessed 21 Mar 2016)

Ye Q (2008) Commodity booms and their impacts on the Western Australian economy: the iron ore case. Resources Policy 33:83–101

Zika M, Erb KH (2009) The global loss of net primary production resulting from human-induced soil degradation in drylands. Ecological Economics 69:310–318

Coordinating Editor: Stephen Murphy

Received: 3 February, 2016; First decision: 12 March, 2016; Revised: 21 April, 2016; Accepted: 22 April, 2016; First published online: 15 June, 2016