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Editorial

Seeds at the forefront: synthesis of the inaugural National Seed Science Forum and future directions in Australian seed science

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Abstract. Seed science is fundamental to many fields of endeavour, from agricultural production, to restoration, and conservation of threatened species and communities. This is especially the case in Australia which has seen hugely increased involvement and outputs from seed scientists across many sectors over the last three decades. This escalation in research is reflected in the program and outcomes of the first National Seed Science Forum that was held in March 2016 and was attended by delegates representing many scientific institutions, industry, non-government organisations and volunteer groups. There were delegates from nine countries, and keynote presentations and workshops by global leaders in seed science. A key outcome of the Forum was the unique opportunity for discussion and collaboration across sectors. Another key outcome of the Forum, the *Seed Science Special Issue* of the Australian Journal of Botany, captures some of the emerging topical research and themes seed scientists are working on. Of particular note is the growth in germplasm conservation of native and agricultural floras, in line with, and at the forefront of, international collaborative efforts. The other strong theme across the Forum is the increasingly sophisticated use of seeds in restoration and the enabling technological advances. Future potential advances in Australian seed science are discussed.

Introduction to Australian seed science and overview of the National Seed Science Forum

Seeds are integral to plant reproduction, dispersal, establishment, adaptation, and persistence. Their study underpins diverse areas of plant science such as agriculture and horticulture, plant conservation, genetics and breeding, and more recently habitat restoration (Fig. 1). Seeds are sometimes underappreciated, but nevertheless important, indeed critical, to human wellbeing as they help to feed (e.g. wheat), clothe (e.g. cotton) and fuel the world (e.g. canola); as well as being the original sources for various pharmaceutical compounds (e.g. caffeine) and spices (e.g. nutmeg), that are a part of our daily lives. In future, their effective and insightful use will be at the forefront of providing some of the solutions to many of the world's challenges – global food security (Bardgett and Gibson 2017), environmental degradation (Svejcar *et al*. 2017), loss of biodiversity (Halley *et al*. 2017) and climate change (Walck *et al*. 2011).

In Australia, studies of seeds of wild species have become increasingly prominent over the past three decades, particularly in the context of biodiversity conservation and land management. Reflecting the rise in extent and diversity of seed science in Australia, in March 2016, the National Seed Science Forum was held at the Australian PlantBank, at the Australian Botanic Garden, Mount Annan, NSW. The Forum was attended to capacity by over 140 delegates from nine countries from government, academia, non-government organisations, industry and volunteer groups who came together to discuss seeds within the four central themes of (1) Dormancy and Germination; (2) Establishment and Management; (3) Seed Storage, Conservation and Utilisation and; (4) Seed Ecology. There were several special events over the course of the Forum. Indigenous panel members discussed cultural dimensions of the collection and use of native plant material and traditional knowledge. A special presentation *The Gift of Seeds, CGIAR Centres and the Global Crop Diversity Trust* was given by The Honourable Tim Fischer AC. The Society for Ecological Restoration Australasia launched their *National Standards for the Practice of Ecological Restoration in Australia* (Standards Reference Group SERA 2017) with guest speaker, then Threatened Species Commissioner, Gregory Andrews, emphasising the importance of biodiversity conservation in Australia. A Masterclass was given by world-leading seed physiologist Dr Christina Walters from the USDA who synthesised decades of research as well as the latest international research to address the perennial seed banking questions: 'How should genebanks dry seeds for long-term storage?', 'How should seed moisture be maintained and monitored?', and 'What longevity do we expect to achieve?'.

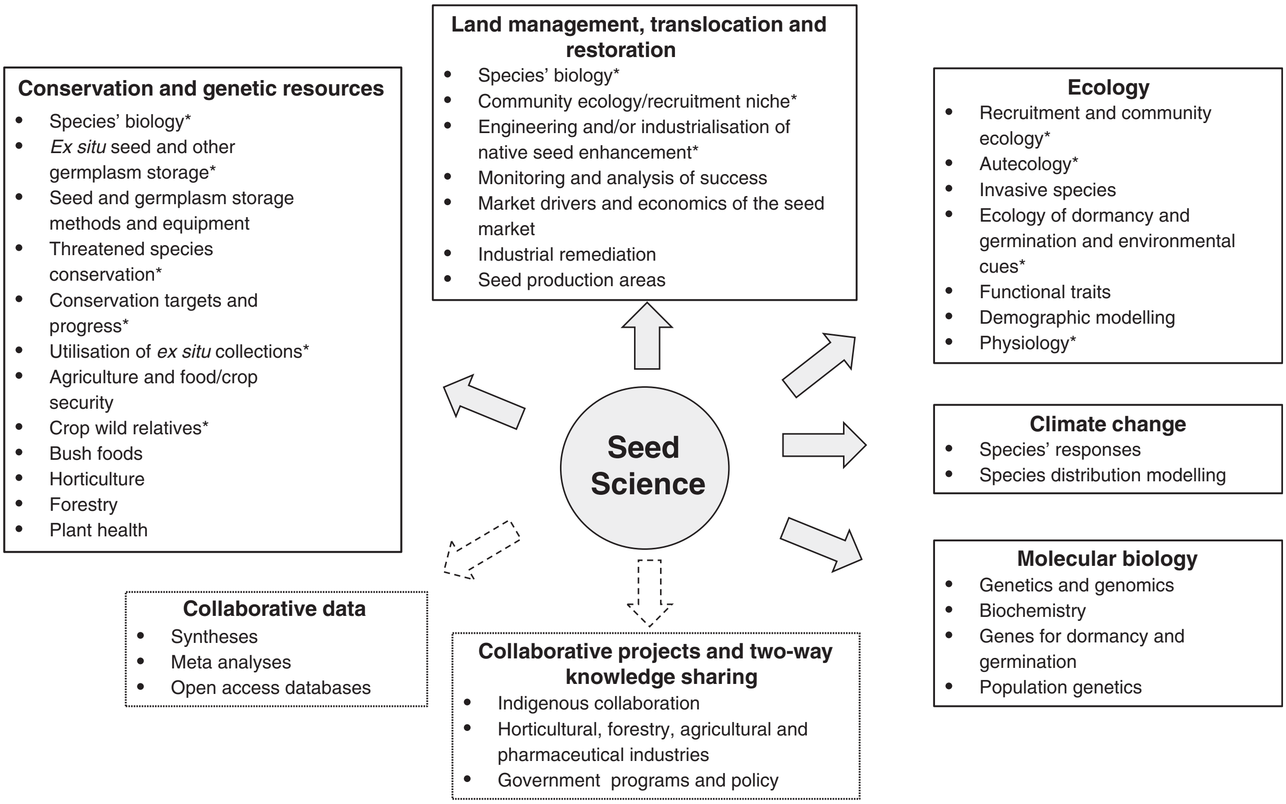

Fig. 1. Conceptual diagram demonstrating that seed science, and the cross-cutting themes of the National Seed Science Forum (1) Dormancy and Germination; (2) Establishment and Management; (3) Seed Storage, Conservation and Utilisation and; (4) Seed Ecology, are fundamental to many fields covered in this special issue (*), and to many other areas of research that are new and emerging, or already published elsewhere (arrows with continuous borders). Future advances across all of these areas will most likely involve greater synthesis and accessibility of data, and engagement and collaboration across multiple sectors (arrows with dashed borders) – with seed science in Australia remaining at the forefront.

A key purpose of the Forum was to bring together people working with seeds across different sectors. Seed scientists, people working in the native and agricultural seed industries, restoration practitioners, students, and volunteers had the opportunity to share the latest research and ideas, discuss contemporary issues, and form new collaborations to advance future conservation, agricultural, and restoration efforts across the country. During the Forum there were 67 oral presentations, and 18 posters displayed, with a significant proportion given by postgraduate students representing universities from most Australian States and Territories. The range of topics was diverse covering seeds and rare and invasive species management, the use of seeds in restoration and direct seeding, as well as seed banking of wild crop relatives, recalcitrant species, and rainforest taxa. Other themes covered included seed germination ecology and issues of germination as they relate to *ex situ* seed bank management, as well as the potential implications of climate-change on *in situ* germination, and seed banking.

One of the key outcomes from the National Seed Science Forum is this *Seed Science Special Issue*, which distils some of the current thinking and contemporary research being pursued in the Australian region. The papers included provide a snapshot of seed science across the country, from the Pilbara in the north west, to the islands of the South Pacific. Of note, is the highly collaborative nature of the work featured. In lieu of a series of smaller articles, the editorial team has encouraged the synthesis of like work across organisations, sectors, and geographic regions resulting in five comprehensive papers by 34 individual authors. Two broad areas of current research that emerged from the Forum were 'seed conservation and genetic resources', and 'seeds in species translocation and landscape restoration', and they are the focus of this special issue.

Seed conservation and genetic resources

Seed science in Australia is responsive to global as well as national and State/Territory strategies for conservation. The *Global Strategy for Plant Conservation* (GSPC) currently aims, by 2020, to incorporate at least 75% of threatened plant species in *ex situ* collections, preferably in the country of origin, with 20% available for recovery and restoration (Target 8), as well as conservation of 70% of the genetic diversity of crops, and their wild relatives and socioeconomically important species (Target 9). Australian organisations have made good progress against these international targets (see various papers in Morgan 2014). Nationally, the Australian Government's *Threatened Species Strategy* Action Plan incorporates many seed-based activities including seed banking and aims to bank all known threatened plant species by 2020 (Department of the

Environment and Energy 2018*a*). Seed banks for wild species have been working to meet such targets and have historically been associated with Botanic Gardens and with the long-term *ex situ* conservation of biodiversity. However, increasingly seed banking initiatives are involving local, national, and multi-national collaborative programs encompassing diverse institutions to coordinate large-scale seed collections for biodiversity protection. In Australia, seed conservation activities have become increasingly coordinated and collaborative at a national scale, through initiatives such as the Millennium Seed Bank Partnership (www.kew.org/science/collections/seed-collection), and the formation of the Australian Seed Bank Partnership (www.seedpartnership.org.au/). Such partnerships are essential to ensure objectives of various seed banking projects are met across the geographically large and variable, and species-rich, Australian region.

Crop wild relatives are one group of plants at the nexus of conservation and agricultural sectors. They have significant conservation value as genetic resources for breeding desirable traits into crop varieties, including plant resistance to pests, diseases, and environmental stress, and increased productivity and nutritional values (Maxted and Kell 2009; Castañeda-Álvarez *et al*. 2016). Considerable attention is being directed towards the capture and conservation of representative germplasm of remaining natural populations of crop wild relatives before they are lost, as part of a global drive to enhance food security and respond to changing climates (Jarvis *et al*. 2008; Dempewolf *et al*. 2014; Castañeda-Álvarez *et al*. 2016). It is estimated that only 5% of crop wild relatives have sufficient germplasm conserved to adequately represent the geographic and ecological variation of the populations (Castañeda-Álvarez *et al*. 2016). A recent analysis of germplasm holdings identifies regions of Australia, particularly the northern tropics of Western Australia, the Northern Territory, and Queensland, as less well recognised hotspots for collecting seeds of high-priority crop wild relatives (Castañeda-Álvarez *et al*. 2016). In their paper in this issue, *Priorities for enhancing the ex situ conservation and use of Australian crop wild relatives*, Norton *et al*. (2017) thoroughly analyse the conservation status of crop wild relatives native to Australia, including a gap analysis of collections for 58 high priority taxa. As the authors point out, Australia is home to close relatives of major food crops including rice (*Oryza* spp.), sorghum (*Sorghum* spp.), soybean (*Glycine* spp.), and many others, but most are severely under-represented in gene banks. With the extent of the natural distribution of many of these species yet to be fully defined, Norton *et al*. (2017) map the potential distribution of these taxa, along with a comprehensive ranking and prioritisation to guide future seed collection programs.

While most *ex situ* conservation is based on banking of orthodox (desiccation tolerant) seeds, research is also focussing on understanding which species among the diverse Australian flora produce seeds with more complex storage behaviour, including recalcitrant seeds (those that are sensitive to desiccation) or seeds that fall somewhere in the spectrum of an intermediate category. Seeds with such non-orthodox storage behaviour either cannot be dried lower than ~10% moisture content, and/or cannot survive subsequent storage at −18°C (or lower), without losing viability rapidly. For species unsuited to seed banking, alternative techniques, such as tissue culture or cryostorage, which often rely on seeds as the initial source of tissue, are being used or further developed (Ashmore *et al*. 2015). The paper by Sommerville *et al*. (2017), *Saving rainforests in the South Pacific: challenges in ex situ conservation*, reviews the seed conservation status of a high priority ecosystem, namely the rainforests of the South Pacific. While smaller in size than the well known rainforests of the Amazon and South-East Asia, the rainforests of the countries and territories of the South Pacific, including Australia and New Zealand, are significant and biodiversity rich in species number and endemism, reflected in the 6 biodiversity hotspots across the region (Mittermeier *et al.* 2011). The paper provides a useful definition of the spectrum of rainforest types found across the region and an analysis of the extent of historical loss, including the recent acceleration of rainforest destruction. Sommerville *et al*. (2017) used a range of authoritative sources, and the results of papers presented by the authors at the National Seed Science Forum, to capture the seed storage behaviour of 1503 genera from 209 families occurring in rainforests across the region. The major finding of this analysis is the lack of information on seed storage behaviour for around 50% of the genera and 25% of families examined, which is likely to be hampering effective *ex situ* conservation. Clearly, there is no one *ex situ* conservation method that suits all species as there is a great range of seed behavioural types within families, even within genera. Therefore, effort put into collecting and banking seeds that are unlikely to survive drying or cold storage may be wasted and that effort would be well spent understanding seed behaviour and using or developing alternative *ex situ* conservation methods for recalcitrant-seeded species. The review also highlights the general lack of *ex situ* conservation capacity outside Australia and New Zealand for non-crop species. Many of the species that have been relatively well conserved outside these countries are important for sustaining communities and economic crop development, and efforts are increasing, focussing on alternative conservation methods including tissue culture and cryostorage. Although not all South Pacific countries were able to be included in this review, the work constitutes the first census of seed conservation potential of rainforest species of the region and provides a framework for future data synthesis that may expand beyond just the rainforest taxa and into other endemic or significant species of the region. The work of Sommerville *et al*. (2017) is an important decision-making resource for the major integrated conservation efforts and partnerships required for rainforests in the region, which generally lack adequate conservation facilities.

Seeds in species-translocation and landscape-restoration

Seeds are the fundamental unit for dispersal and regeneration for most flowering plants. As such, they are commonly the units used for translocating individual threatened species to new or previously degraded sites, or for restoring components of whole plant communities that may have been removed from the landscape e.g. due to mining or historical land clearing. The ecological restoration of land impacted by mining operations is a prominent conservation concern in Australia where individual mine footprints vary in size from 100s to 1000s of hectares, and the cumulative effects of tens, or even hundreds, of individual mine sites located within a biogeographic region can be substantial (Lamb *et al*. 2015). Mining can also impact geological formations that are unique to the surrounding landscape; Banded Ironstone formations in the south-west of Western Australia being one example. Such landforms can comprise biodiverse vegetation assemblages that are unique, with high levels of plant species or plant community endemism and, in some cases, rarity (Gibson *et al*. 2010). Protection of populations of rare plant species or communities against decline due to various threatening processes such as mining or the fragmentation caused by past land use is paramount. Using seeds to achieve conservation and restoration aims is increasingly common and requires a detailed understanding of many aspects of seed biology, as evidenced by the papers of Turner *et al*. (2017), Erickson *et al*. (2017), and Vening *et al*. (2017) in this issue.

The paper by Turner *et al*. (2017), *Seed ecology informs restoration approaches for threatened species in water-limited environments: a case study on the short-range Banded Ironstone endemic* Ricinocarpos brevis *(Euphorbiaceae)*, considers how seed ecophysiology contributes to the management of translocation programs for threatened species. Through a review of published studies, it is clear that the direct sowing of seeds is rarely the primary means of plant re-introduction in translocations. The authors propose that seed regenerative traits are rarely defined for these translocations, and, consequently, seedling establishment is almost universally poor. This study outlines a trait-based approach to seed translocation using the example of the threatened species *Ricinocarpos brevis*. In particular, the study pairs data on seed dormancy and germination traits with data on the environmental conditions at the translocation sites to define the window of opportunity for seedling establishment. These data will inform future translocation efforts to manage and protect the species during mining operations. The paper provides a unique example of how translocation success for some of Australia's most threatened species can be greatly increased by understanding the seed biology and ecology of a species and the influence of the abiotic environment on seed germination and establishment.

Multiple species, rare and common, may be impacted by mining. In their paper, *Benefits of adopting seed-based technologies for rehabilitation in the mining sector: a Pilbara* perspective, Erickson *et al*. (2017) discuss a long-term partnership between ecological scientists and environmental staff in the mining sector. The authors detail how scientific findings have informed management practices for mine site rehabilitation. For example, a focus on seed procurement, including the information captured during seed collection and data management procedures, has ensured that sufficient seed of verified origin and quality is available for up to five years' worth of rehabilitation. Seed dormancy and germination traits – functional attributes of seeds that are core to initiating plant regeneration – have been resolved for over 100 species of the Pilbara bioregion and detailed data on these traits are provided. Ongoing research to develop seed enhancement technologies is described, as is a significant effort to characterise and enhance the physical, chemical, and biological properties of various substrates (e.g. topsoil, waste rock) representative of the rehabilitation sites. This research highlights the crucial need to understand the soil-seed interface to guide modification of the seed, or the soil, or both, to optimise the regenerative niche and the seed establishment opportunity. In this paper, the benefits of building multi-disciplinary teams to solve complex restoration challenges are evident, as is the value to all parties derived from multi-disciplinary research partnerships with industry.

A third paper in this translocation and restoration theme is also the result of a research partnership with industry and focusses on seeds in the context of improving restoration of threatened plant communities, namely grassy woodlands in eastern Australia. Due to past clearing and land use changes <1% of the previous extent of, for example, the 'White Box - Yellow Box – Blakely's Red Gum Grassy Woodlands and Derived Native Grasslands' community remains as intact, high quality remnants (Department of the Environment and Energy 2018*b*). Increasing the diversity of the understorey of degraded grassy woodlands is a high priority (Prober and Thiele 2005) but is difficult to achieve as a large portion of the understorey is regarded as difficult to germinate. Although some studies and anecdotal evidence were available, research into the dormancy and germination of many understorey species was previously unpublished or did not assess multiple treatments to quantitatively determine which treatments achieve the highest germination. In *Seed dormancy and germination of three grassy woodland forbs required for diverse restoration*, Vening *et al*. (2017) examine seed dormancy of the three study species *Dianella longifolia*, *D. revoluta*, and *Stackhousia monogyna*, relatively common and widespread understorey forbs that have proven difficult to germinate for restoration purposes. The authors determine that seeds of all species possess physiological dormancy, and describe the germination responses to a range of treatments to increase the opportunities for nursery production of plants and for the establishment of seedlings following direct seeding. This paper demonstrates how seed science can contribute information to assist restoration programs in achieving diversity targets.

Emerging themes and future directions

Plants support all life on Earth. Their seeds are fundamental to the health of the planet and are integral to human survival and prosperity. With the Earth's sixth mass extinction documented to be underway (Ceballos *et al*. 2017), and habitat destruction recognised as threatening more terrestrial organisms than any other process (Kingsford *et al*. 2009), plant seeds and the science underpinning their use clearly come to the fore.

Seed banking is a powerful tool for conservation. Seed banks provide a safety net for securing genetic, species, and community-level diversity of plants facing myriad threatening processes. The success of seed banking lies in the ability of seeds of the majority of species to survive in the dry state for many years, decades, or even centuries. But the sheer diversity of the Australian flora constantly tests the ingenuity of those engaged in seed conservation. With biological diversity comes a diversity in seeds' responses to the standardised environmental conditions employed in seed banking. Defining and predicting seed storage behaviour continues to be an area of need – as seed collections increase in size, curation activities, such as the setting of viability testing schedules, become increasingly complex. In particular, identifying desiccation tolerant but short-lived seeds (Walters 2015) — such as orchids (Hay *et al*. 2010) and some rainforest and alpine species (Mondoni *et al*. 2011; Sommerville and Offord 2015) — along with desiccation sensitive seeds that require more specialised storage techniques (Hamilton *et al*. 2013), are high priorities for seed bank management.

Seed scientists also have a major role to play in supporting habitat restoration through the sourcing and provision of seeds, and through developing expertise in seed-based propagation. Contemporary restoration programs aim to restore biodiverse plant communities at the landscape scale, meaning the return of tens to hundreds of species will be required in many ecosystems, and there is increasingly a focus on enhancing the diversity of understorey in restoration programs (Miller *et al*. 2017). Thus, determining seed dormancy and germination traits – historically perhaps the primary areas of research focus in Australia – remains a fundamental need. Seeds are inherently plastic, with complexity of function apparent at any level (e.g. within and between species, plant populations, individual plants and seed populations) (Cochrane *et al*. 2015*b*). Dormancy is a predominant trait in many floras, and complex dormancy is common in the Australian flora (Merritt *et al*. 2007). Increasingly, an ecologically-guided approach is resolving dormancy and germination characteristics, particularly by considering the biotic and abiotic factors influencing regeneration and seedling establishment in the field. Regeneration traits of species can be used to inform and better understand the patterns and processes in plant community ecology for restoration and threatened species conservation (Jiménez-Alfaro *et al*. 2016; Merino-Martín *et al*. 2017). Such seed (and plant) trait data have yielded many discoveries on the ecology and evolution of Australian plants (Moles 2018) and ongoing work to understand the influence of such morphological and physiological traits with key life history stages such as dispersal (e.g. Guja *et al*. 2014), stress tolerance, recruitment and establishment will likely yield even more discoveries.

Seed regeneration traits can also be employed to study the effects of changing climates on species' distributions and can in fact enhance species distribution models that estimate habitat preferences or predict distribution (Guillera-Arroita *et al*. 2015). Such traits enable researchers to move beyond approaches that correlate the absence/presence of a species with relevant environmental covariates, which arguably have somewhat limited value when attempting to understand the underlying drivers of species' habitat preference (Pacifici *et al*. 2015). Seed traits and environmental thresholds for regeneration can also further understanding of species' vulnerabilities to climate change. For example, recent studies have found that as soil temperatures increase or fire regimes change there will be measurable changes in the level and extent of seed dormancy within-species, as well as possible deleterious changes in the capacity of seeds to persist in the soil seed bank (Ooi *et al*. 2012; Hoyle *et al*. 2013; Ooi *et al*. 2014). Australia's alpine regions are predicted to experience significant changes in temperature over the next few decades, with the effects on soil seed banks and seed regeneration potentially resulting in profound changes to the composition of vegetation communities (Hoyle *et al*. 2013; Sommerville *et al*. 2013; Hoyle *et al*. 2014). In light of these changes, the ability to identify which species are likely most sensitive to warming or drought (Cochrane *et al*. 2014*a, b*; Cochrane *et al*. 2015*a, b*; Cochrane 2016; Cochrane 2017) will allow for informed development of conservation strategies that prioritise conservation actions for at-risk species.

Knowledge of seed regeneration traits also feeds into the development of seed enhancement technologies such as priming, coating, and pelleting (Pedrini *et al*. 2017) that are increasingly the focus of research to improve seedling establishment under field conditions (e.g. Madsen *et al*. 2016; Erickson *et al*. 2017). The challenge remains, for many species, to develop seed treatments that are reliable, repeatable, and applicable to large-volumes of diverse seed collections required for landscape scale restoration (Merritt and Dixon 2011).

Related to large-scale, seed-based restoration, as well as rare species translocation and management, is the provision of sufficient quantities of seeds (Merritt and Dixon 2011; Broadhurst *et al*. 2015*a*, 2015*b*; Broadhurst *et al*. 2016). The establishment of seed production areas (SPA) to enhance the quantity and quality of seeds is a key part of the solution (Broadhurst *et al*. 2015*a*, 2015*b*; Broadhurst *et al*. 2016; Nevill *et al*. 2016). Seed production areas allow for the large-scale production of seeds of species in high demand for restoration, or those difficult to source, and temper the potential for overharvesting of wild plant populations (Broadhurst *et al*. 2015*b*; Nevill *et al*. 2016). They may also facilitate production of seeds of threatened species for meaningful larger-scale translocation or restoration programs (Offord *et al*. 2004; Cochrane *et al*. 2007). Some unresolved aspects of SPA include the selection of appropriate genotypes for source material (Prober *et al*. 2015), the design of SPA to maximise genetic fidelity of seeds produced, and the consequences of production processes (e.g. irrigation, fertiliser, harvesting) or maternal and climate effects on seed quality and regenerative traits (Broadhurst *et al*. 2016; Nevill *et al*. 2016).

The consolidation, management, and sharing of data, preferably data collected using agreed standardised methods and formats, is fundamental to guide conservation targets and actions for threatened species and communities. As an example, in 2015 the Federal Government launched Australia's first *Threatened Species Strategy* centred upon science, action and partnership; which aims by 2020 to secure all of Australia's known threatened flora in conservation seed banks. This equates to collection and storage of seeds from well over 1200 species – the majority lacking seed biological knowledge (Cochrane *et al*. 2002; Offord *et al*. 2004; Department of the Environment and Energy 2018*c*). Effective collection and curation of these banked seeds and their future use in translocation will require data and knowledge of many characteristics including plant phenology and fecundity, seed storage, dormancy and germination behaviour, habitat requirements and more. While there is some way to go to achieve a database that captures relevant seed traits (other than seed mass) in a format accessible to researchers and conservation planners, online resources are currently available through the Australian Seed Bank Partnership (http://www.seedpartnership.org.au/) and the associated Atlas of Living Australia 'Australian Seed Bank' website (http://asbp.ala.org.au/), Tasmania's SeedSafe program (http://gardens.rtbg.tas.gov.au/tscc-germination-database/), the South Australian Seed Conservation Centre (http://saseedbank.com.au/), the Centre for

Australian National Biodiversity Research and Australian National Botanic Gardens' 'Seed Image Library' and associated trait database (http://www.anbg.gov.au/photo/; Clinton and Guja 2016) and the Seed Information Database (http://data.kew.org/sid/) managed by the Royal Botanic Gardens Kew. Furthermore, many seed banking institutions maintain their own publicly available databases or can supply information upon request. These databases contain a wealth of information including germination and seed dormancy records, seed storage behaviour, seed dispersal and seed mass, amongst other attributes.

The ideas and concepts captured in the papers within this *Seed Science Special Issue* are just a small snapshot of the work currently under way across Australia, but they highlight the depth of expertise present in the Australian seed science community. We hope that this *Seed Science Special Issue* will provide further impetus for the formation of a common national framework for studying, documenting and reporting seed research, and for the formulation of nation-wide collaborative research programs. It is our hope that by combining scientific understanding and practical experience, including greater involvement and knowledge sharing with various groups, we can help shape policy and practice that address critical conservation challenges and protect Australia's unique biodiversity.

Conflicts of interest

All authors acknowledge that there is no conflict of interest.

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