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Seed science in Australasia: regionally important, globally relevant

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ABSTRACT

The crises of biodiversity loss, climate change and food security are challenges faced by the conservation and agriculture sectors. We outline, via presentations from the Australasian Seed Science Conference, how seed science is addressing these challenges. Research is focused on practical solutions for seed bank management, seed use and biodiversity conservation. Emerging trends include understanding the role of seed microbiota on plant performance and the roles of seeds in society and culture.

Keywords: genebank, germplasm, plant conservation, restoration, seed biology, seed testing, seed traits, seedbank.

Introduction

Seed science is fundamental to addressing global challenges including biodiversity loss, climate change, food security, sustainable development and restoration (Brussaard *et al.* 2010; Jarvis *et al.* 2010; Ceballos *et al.* 2017; Ripple *et al.* 2020; World Economic Forum 2020; Westwood *et al.* 2021; Goodale *et al.* 2023; Schmitz *et al.* 2023). Seed collection and storage, the supply of quality seeds at the right place and time, and developing our understanding of seed biology to inform conservation and food production are critical areas of research to address such challenges (Baskin and Baskin 2014; Walters and Pence 2021; Colville *et al.* 2022; Ooi *et al.* 2022).

Australasian Seed Science Conference (ASSC)

A snapshot of regional and international seed science was presented virtually from 6 to 10 September 2021 at the Australasian Seed Science Conference (ASSC), hosted by the Australian Seed Bank Partnership and Australian National Botanic Gardens, Canberra. The conference, attended by 425 participants from 34 countries, reflected the breadth of seed science globally. The academic programme of 7 keynotes, 61 presentations, 17 posters and 3 workshops highlighted enormous progress in the Australasian region since the inaugural conference in 2016 (Offord *et al.* 2017). The conference highlighted stronger information and technology exchange between the native seed and agricultural seed sectors.

This *Special Issue* of the *Australian Journal of Botany* presents a selection of papers from the ASSC highlighting current and emerging directions in seed science. Here, we summarise key conference themes and outline emerging directions and questions for future seed conservation and research across Australasia. Additional papers presented at ASSC have been published in a special issue of *Australasian Plant Conservation*, the quarterly bulletin of the Australian Network for Plant Conservation (volume 31(2)).

Key themes from the Australasian Seed Science Conference

Seed biology and evolutionary ecology

Recent reviews highlight numerous functional traits that can affect regeneration processes (Saatkamp *et al.* 2019). The ASSC demonstrated that understanding dormancy, germination and underlying functional traits are topical areas of research globally. The *keynote presentation from* Si-Chong Chen demonstrated trait functions across multiple scales. Chen uncovered how smaller seeds invest proportionally more biomass in protective tissues than larger seeds, in agreement with established ideas that small seeds may have advantages in physical defence. Recent studies of seed traits such as resting metabolic rate (Dalziell and Tomlinson 2017), polyploidy (Guja *et al.* 2021) and germination speed (Lewandrowski *et al.* 2021) are revolutionising our understanding of functional traits that shape plant reproductive strategies and seed longevity. Alvarez *et al.* (2023) explored plant and seed traits that may be related to heat wave responses; critical work given the increased frequency and severity of heat waves. Norton *et al.* (2021) demonstrated characterisation of traits or genes to enable selection for agricultural breeding programmes, and Barrero and Higgins (2021) identified traits that improved crop resilience to pests to advance agriculture and food production.

Research continues to investigate how germination or reproduction responses are related to multiple environmental factors such as temperature stress (Notarnicola *et al.* 2021), moisture stress (Emery *et al.* 2021; Schultz *et al.* 2021) and seasonal change (Rosbakh *et al.* 2021). These new insights show how the regeneration niche may contribute to species distribution under climate change. For example, Hoyle *et al.* (2023) demonstrated that light quality, which is likely to be altered by reduced cloud immersion, impacts the germination responses of tropical montane cloud forest species from far-north Qld. Coupled with innovative technology like temperature gradient plates (Collette *et al.* 2021), research can test multiple levels of factors and enable high resolution investigations of environmental drivers of germination. Such data are also requiring developments in statistical analysis methods as discussed in the workshop 'Analysing Seed Data with R' (Rosbakh *et al.* 2021).

The seed microbiome is an emerging research direction evident in global research (Nelson *et al.* 2018) and the ASSC programme. Mertin *et al.* (2023) synthesised seed microbiome findings for several native Australian species including potential significance and application to improve seedling establishment in conservation and restoration.

Seed and gene bank management

Reviews of the quantity or representativeness of collections stored (Westengen *et al.* 2013; Liu *et al.* 2018), and their physiological quality or viability (Liu *et al.* 2020), demonstrate that gene bank management practices are effective for conserving a large diversity of species long-term. Across nearly 1750 global gene banks that secure a significant proportion of the world's biodiversity and crop diversity (Westengen *et al.* 2013; Liu *et al.* 2020; Walters and Pence 2021), further advances in collection management are required to ensure future needs are met, with research continuing to improve practices for a broader number of species and requirements.

Comparisons of different gene banks provide useful insights to guide future work (Hay and Probert 2013; Westengen *et al.* 2013) demonstrated by the *keynote of Sally Norton and Elinor Breman*, comparing agricultural (Australian Grains Genebank) and conservation facilities (Millennium Seed Bank). Improved methods to maximise seed quality and longevity are in development (Jawad *et al.* 2021; Abdul Rahman and Sohaimi 2021), and gene bank manager's networks and toolkits are growing (Latifah *et al.* 2021; Cai *et al.* 2021; Crawford *et al.* 2021; Irawanto *et al.* 2021). Fundamental seed banking techniques, relevant to individual research and long-term conservation programmes, were shared in the 'Seed banking 101' workshop. Additionally, there are ongoing global efforts to share gene banking information (such as seed longevity or germination data) through aggregated databases (Liu *et al.* 2018; Falster *et al.* 2021; Fernández-Pascual *et al.* 2023). New technologies being trialed by many gene banks include digitisation and databasing of seed images (Kingsley 2021) coupled with machine learning and computer vision to assist in phenotyping and biosecurity (Schmidt-Lebuhn 2021).

The adaptability and diversity of Australasian flora tests the ingenuity of those engaged in plant conservation. Biological diversity drives a range of variations and responses to the standardised conditions currently employed in seed banking (Hu 2021; Funnekotter *et al.* 2021). Sommerville *et al.* (2023) provided a cautionary example demonstrating that some Australian rainforest species have seeds that are short-lived in standard storage conditions. New global frameworks have been developed for categorising such 'exceptional species', that require alternative methods beyond conventional seed banking (Pence *et al.* 2022*a*, 2022*b*). The application of alternatives to conventional seed storage across Australasian species is gaining momentum (Ballesteros and Pritchard 2021; Chong *et al.* 2021; Hardstaff *et al.* 2021), requiring an extension of 'seed banking' to encompass *ex situ* conservation more broadly. This was investigated in-depth through the Australian Academy of Science *Fenner Conference on the Environment* 'Exceptional Times, Exceptional Plants' (Martyn Yenson *et al.* 2023). A full range of *ex situ* methods will be needed to address the current rates of biodiversity loss.

Seed sourcing and end-use

Collecting viable and genetically diverse seeds, in the right amount and at the right time, is a critical aspect of gene banking that ensures seed can be used (Goodale *et al.* 2023). Research into seed sourcing and end use is increasingly focused on genetic diversity, restoration and translocation as well as sector-specific approaches to seed conservation and use.

The *keynote presentation* by Robert Henry highlighted rapid technical advances allowing application of genomic analysis to guide the collection and use of genetic resources, and utilisation of Australian plant resources in crop improvement and climate adaptation. Identifying the genetic basis of desirable plant traits enhances the ability to utilise these traits in breeding and production, building the case for genome sequencing of as many species as possible. Genetic analysis can also provide empirical data to develop targeted seed sampling strategies that capture as much new genetic diversity as possible in *ex situ* conservation. Van der Merwe *et al.* (2023) extend this, advocating for the storage of maternal lines to increase potential conservation applications. The utility of genetic analyses was demonstrated in biosecurity screening of imported crop seeds for virus detection (Maina *et al.* 2021).

The publication of key documents by the Australian Network for Plant Conservation illustrates how evidence-based guidelines such as the Florabank (Commander and Driver 2021) and Germplasm Guidelines (launched at the ASSC; Martyn Yenson *et al.* 2021) can support practitioners. Research can also support development of seed industry accreditation schemes such as the successful Western Australian-based example (Mikli 2021). Such guidelines are increasingly important given the scale of restoration occurring globally and regionally (Goodale *et al.* 2023). The need to produce large amounts of seed, and maximise the diversity of species available for restoration is critical (Gibson-Roy 2021), as is the need to provide seeds that will germinate and establish readily (Merritt *et al.* 2021; Ruiz Talonia 2021) or produce income for local communities (So and Jalonen 2021). Erickson *et al.* (2023) demonstrate the ability of research to better restore landscapes and species that face severe establishment constraints.

Seeds in culture and society

Although native wild plant species have been used by people for millennia, their introduction into broader scale agriculture is an emerging field (Benlioğlu and Adak 2019; Müller *et al.* 2021), including in Australasia (Jacob *et al.* 2021; Bell *et al.* 2021). Gene banks are exploring frameworks that promote two-way collaboration and respect Indigenous knowledge and culture (Janke 2021) and the *keynote* of Terry Janke demonstrated tangible ways to continue these developments. Gene banks also need to appropriately navigate access and benefit sharing under international conventions, as discussed by Brad Sherman in his *keynote*. This spirit of collaboration and sharing among community gardens, community organisations (Raneng and Pickering 2021; Sauer 2021) and seed banks has generated powerful partnerships (North *et al.* 2021), regional and national networks (Frost 2021; Wrigley 2021), and impactful international examples of safeguarding crop diversity and enabling reconstitution of collections. The example of the ICARDA genebank in Syria was detailed by Ola Westengen's *keynote* (Westengen *et al.* 2020).

Sharing stories and learning about historical, socio-cultural and legal practices of seed conservation, use, exchange, repatriation, and access and benefit sharing (including collaborations between traditional use, community, and *ex situ* seed banks and gene banks) is a significant and growing area.

Seed and gene bank facilities and capability in Australia

Across Australia there are 14 major public seed and gene banks (Martyn Yenson *et al.* 2021; Fig. 1) estimated to hold over 300 000 accessions of over 14 000 species important for biodiversity conservation, agriculture and forestry. Growth in collaboration between agricultural, wild species genebanks, and broader cultural institutions is increasing (Martyn Yenson *et al.* 2021). This paves the way for establishment of greater networks across the region, including gene banks (agricultural, forestry, restoration) and access to expertise (technical and seed testing groups). As the network grows, opportunities for training and development will continue to build. The growth of the strong Early- to Mid-Career Researcher network in Australasian seed science has already resulted in significant and impactful research, as reviewed by Everingham *et al.* (2023).

Summary: seed science and conservation into the future

Seeds are fundamental to the conservation and restoration of threatened species and communities (Walters and Pence 2021), responses to climate change (Fernández-Pascual *et al.* 2019; Galluzzi *et al.* 2020), restoration of plant diversity (Goodale *et al.* 2023), and are the primary basis for human sustenance. Seed science, access to data generated from such research, and collaboration across disciplines are therefore critical to securing our future in a changing world (Breman *et al.* 2021). Research presented at the recent ASSC strongly focused on both the direct (e.g. temperature) and indirect impacts of climate change (e.g. shifting fire regimes, light quality, pest and disease patterns), and how seed traits may contribute to a better understanding of outcomes for both native and agricultural species. A novel aspect of current research is the incorporation of understudied seed traits, multiple environmental factors and their interactions, many of which will inform understanding of the regeneration niche and management under climate change. Also emerging, is the utilisation of agricultural knowledge of characters such as ploidy, seed physiology or the seed microbiome, creating new understanding of persistence and conservation of wild species. New techniques such as cryopreservation for 'exceptional' and other significant species are predicted to increase, alongside the application of digitisation and machine learning tools for seed identification and collection management. Genetic improvements through plant breeding and

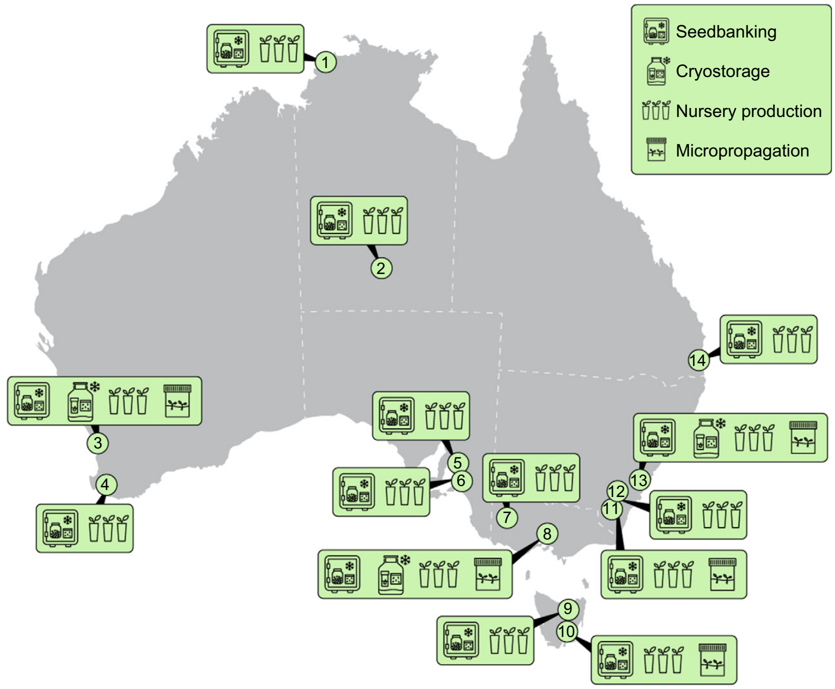

Fig. 1. Location of major *ex situ* conservation facilities for Australian flora, including Australian Seed Bank Partnership Partners, the Australian Grains Genebank and Australian Pastures Genebank (both storing crop wild relatives), and major forestry seed banks such as the Australian Tree Seed Centre (storing conservation collections of native species). (Source: Martyn Yenson *et al.* 2021; Wrigley and Desmond 2023).

production are a focus for improving seed sourcing or end use. Alongside research, is the growing need for the development of seed accreditation schemes to enable improved restoration and biodiversity outcomes, and new ways to scale up seed production for native plant species. Interest in native plant species to transform agriculture is also increasing, providing opportunities to co-design projects and highlight Indigenous knowledge. It will be imperative that developments include culturally appropriate collection of information and germplasm, while strengthening application of policies such as the Nagoya Protocol.

Trends such as these lead to several clear questions for future work. These include: (1) seed biology – which seed traits are important for improving our prediction of plant species' responses to shifting climatic and disturbance conditions, and subsequent community assemblage and structure? Does interaction between seed traits and other trophic groups, for example within the seed microbiome, have implications for seedling establishment and population persistence? Which seed traits are important for understanding seed storage behaviour? (2) Seed bank management – how can we improve information exchange among diverse gene banks? How can new technologies help streamline collection management or characterise new traits? (3) Seed end use – how can we identify and utilise genetic traits for conservation, plant breeding and plant production? How can we sustainably collect and store gene bank accessions and data to increase utility and facilitate use? (4) Seeds in culture and society – how can we effectively translate new science into practice? How do we store and use seeds and germplasm in culturally appropriate or sensitive ways?

References

Abdul Rahman SM, Sohaimi SSB (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Alvarez PR, Krix DW, Offord CA, Murray BR (2023) Impact of extreme heatwaves and life-history traits on seed germination responses in Cumberland Plain Woodland native plant species. *Australian Journal of Botany* **71**(7), 395–405. doi:10.1071/BT22117

Ballesteros D, Pritchard HW (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Barrero J, Higgins TJ (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Baskin CC, Baskin JM (2014) 'Seeds: ecology, biogeography, and evolution of dormancy and germination.' (Academic Press: San Diego, CA, USA)

Bell T, Pattison A, Keitel C, Khoddami A, Cross R (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Benlioğlu B, Adak MS (2019) Importance of crop wild relatives and landraces genetic resources in plant breeding programmes. *Journal of Experimental Agriculture International* **37**(3), 1–8. doi:10.9734/jeai/2019/v37i330268

Breman E, Ballesteros D, Castillo-Lorenzo E, Cockel C, Dickie J, Faruk A, O'Donnell K, Offord CA, Pironon S, Sharrock S, Ulian T (2021) Plant diversity conservation challenges and prospects – the perspective of botanic gardens and the Millennium Seed Bank. *Plants* **10**(11), 2371. doi:10.3390/plants10112371

Brussaard L, Caron P, Campbell B, Lipper L, Mainka S, Rabbinge R, Babin D, Pulleman M (2010) Reconciling biodiversity conservation and food security: scientific challenges for a new agriculture. *Current Opinion in Environmental Sustainability* **2**(1–2), 34–42. doi:10.1016/j.cosust.2010.03.007

Cai J, Yang X, Zhang T, Li D (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Ceballos G, Ehrlich PR, Dirzo R (2017) Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. *Proceedings of the National Academy of Sciences of the United States of America* **114**, E6089–E6096. doi:10.1073/pnas.1704949114

Chong C, Grigg A, Guja L (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Collette J, Sommerville K, Lyons M, Offord C, Errington G, Newby Z-J, von Richter L, Emery N (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Colville L, Hilhorst HWM, Pritchard HW (2022) Editorial to the special issue on Seed Innovation Systems for the 21st Century. *Seed Science Research* **32**, 115–117. doi:10.1017/S0960258522000241

Commander L, Driver M (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Crawford A, Kelly A, Cochrane A (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Dalziell EL, Tomlinson S (2017) Reduced metabolic rate indicates declining viability in seed collections: an experimental proof-of-concept. *Conservation Physiology* **5**(1), cox058. doi:10.1093/conphys/cox058

Emery N, Offord C, Collette J (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Erickson TE, Dwyer JM, Dalziell EL, James JJ, Muñoz-Rojas M, Merritt DJ (2023) Unpacking the recruitment potential of seeds in reconstructed soils and varying rainfall patterns. *Australian Journal of Botany* **71**(7), 353–370. doi:10.1071/BT22141

Everingham SE, Chen S-C, Lewandrowski W, Plumanns-Pouton E (2023) Novel and emerging seed science research from early to middle career researchers at the Australasian Seed Science Conference, 2021. *Australian Journal of Botany* **71**(7), 371–378. doi:10.1071/BT22101

Falster D, Gallagher R, Wenk EH, *et al.* (2021) AusTraits, a curated plant trait database for the Australian flora. *Scientific Data* **8**, 254. doi:10.1038/s41597-021-01006-6

Fernández-Pascual E, Mattana E, Pritchard HW (2019) Seeds of future past: climate change and the thermal memory of plant reproductive traits. *Biological Reviews* **94**, 439–456. doi:10.1111/brv.12461

Fernández-Pascual E, Carta A, Rosbakh S, Guja L, Phartyal SS, Silveira FAO, Chen S-C, Larson JE, Jiménez-Alfaro B (2023) *SeedArc*, a global archive of primary seed germination data. *New Phytologist* **240**, 466–470. doi:10.1111/nph.19143

Frost D (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Funnekotter B, Bunn E, Mancera RL (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Galluzzi G, Seyoum A, Halewood M, López Noriega I, Welch EW (2020) The role of genetic resources in breeding for climate change: the case of public breeding programmes in eighteen developing countries. *Plants* **9**(9), 1129. doi:10.3390/plants9091129

Gibson-Roy P (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Goodale UM, Antonelli A, Nelson CR, Chau MM (2023) Seed banks needed to restore ecosystems. *Science* **379**(6628), 147. doi:10.1126/science.adg2171

Guja L, Wallace MJ, Stevens AV, Chan JCS, Chen SH, Ooi MKJ, Schmidt-Lebuhn A, Godfree RC, Broadhurst LM, Nicotra A (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Hardstaff L, Sommerville K, Funnekotter B, Bunn E, Mancera R, Offord C (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Hay FR, Probert RJ (2013) Advances in seed conservation of wild plant species: a review of recent research. *Conservation Physiology* **1**(1), cot030. doi:10.1093/conphys/cot030

Hoyle GL, Stevens AV, Guja LK, Sommerville KD, Worboys S, Crayn DM (2023) Sunlight and red to far-red ratio impact germination of tropical montane cloud forest species. *Australian Journal of Botany* **71**(7), 326–339. doi:10.1071/BT22126

Hu X-J (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT)

Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Irawanto R, Hardwick K, Latifah D, Angio MH, Renjana E, Firdiana ER, Ningrum LW (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Jacob SS, Smyth H, Flanagan B, Williams B, Gidley M (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Janke T (2021) 'True tracks: respecting Indigenous knowledge and culture.' (NewSouth Publishing: Sydney, NSW)

Jarvis A, Upadhyaya HD, Gowda CLL, Agrawal PK, Fujisaka S, Anderson B (2010) 'Climate change and its effect on conservation and use of plant genetic resources for food and agriculture and associated biodiversity for food security.' Monograph. (Food and Agriculture Organization of the United Nations: Rome, Italy)

Jawad R, Ellis R, Hay F, Yazbek M (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Kingsley N (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Latifah D, Hardwick K, Zuhri M, Widjaya AH, Irawanto R, Darmayanti AS, Kuswantoro F, Lestari D, Handini E (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Lewandrowski W, Elliott C, Stevens J, Tomlinson S, Miller B, Dolin C, Anderson NS, Turner S (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Liu U, Breman E, Cossu TA, *et al.* (2018) The conservation value of germplasm stored at the Millennium Seed Bank, Royal Botanic Gardens, Kew, UK. *Biodiversity and Conservation* **27**, 1347–1386. doi:10.1007/s10531-018-1497-y

Liu U, Cossu TA, Davies RM, *et al.* (2020) Conserving orthodox seeds of globally threatened plants ex situ in the Millennium Seed Bank, Royal Botanic Gardens, Kew, UK: the status of seed collections. *Biodiversity and Conservation* **29**, 2901–2949. doi:10.1007/s10531-020-02005-6

Maina S, Zheng L, Norton S, King S, McQueen V, Rodoni B (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Martyn Yenson AJ, Offord CA, Meagher PF, Auld T, Bush D, Coates DJ, Commander LE, Guja LK, Norton SL, Makinson RO, Stanley R, Walsh N, Wrigley D, Broadhurst L (2021) 'Plant Germplasm Conservation in Australia: strategies and guidelines for developing, managing and utilising *ex situ* collections.' 3rd edn. (Australian Network for Plant Conservation: Canberra, ACT) Available at https://www.anpc.asn.au/plant-germplasm/

Martyn Yenson AJ, Sommerville KD, Guja LK, Merritt DJ, Dalziell EL, Auld TD, Broadhurst L, Coates DJ, Commander L, Crawford AD, Emery NJ, Funnekotter B, Knapp Z, Makinson RO, Monks L, Wrigley D, Offord CA (2023) *Ex situ* germplasm collections of exceptional species are a vital part of the conservation of Australia's national plant treasures. *Plants, People, Planet.* doi:10.1002/ppp3.10421

Merritt D, Munoz Rojas M, Turner S, Dalziell E, Dwyer J, Kildisheva O, Lewandrowski W, Erickson T (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Mertin AA, Philpott M, Blackall LL, French K, Liew ECY, van der Merwe MM (2023) Integrating seed microbiome knowledge into restoration and *ex situ* conservation of native Australian plants. *Australian Journal of Botany* **71**(7), 379–394. doi:10.1071/BT22109

Mikli M (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Müller JV, Cockel CP, Gianella M, Guzzon F (2021) Treasuring crop wild relative diversity: analysis of success from the seed collecting phase of the 'Adapting Agriculture to Climate Change' project. *Genetic Resources and Crop Evolution* **68**, 2749–2756. doi:10.1007/s10722-021-01229-x

Nelson EB, Simoneau P, Barret M, *et al.* (2018) Editorial special issue: the soil, the seed, the microbes and the plant. *Plant and Soil* **422**, 1–5. doi:10.1007/s11104-018-3576-y

North T, Grigg A, Wilson M, Moyle F (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Norton S, Hayden M, Tibbets J, Kant S, Panozzo J (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Notarnicola R, Nicotra A, Kruuk L, Arnold P (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Offord CA, Guja LK, Turner SR, Merritt DJ (2017) Seeds at the forefront: synthesis of the inaugural National Seed Science Forum and future directions in Australian seed science. *Australian Journal of Botany* **65**, 601–608. doi:10.1071/BTv65n8_ED

Ooi MKJ, Tangney R, Auld TD (2022) Fire and regeneration from seeds in a warming world, with emphasis on Australia. In 'Plant regeneration from seeds'. (Eds CC Baskin, JM Baskin) pp. 229–242. (Academic Press)

Pence VC, Bruns EB, Meyer A, Pritchard HW, Westwood M, Linsky J, Gratzfeld J, Helm-Wallace S, Liu U, Rivers M, Beech E (2022*a*) Gap analysis of exceptional species – Using a global list of exceptional plants to expand strategic ex situ conservation action beyond conventional seed banking. *Biological Conservation* **266**, 109439. doi:10.1016/j.biocon.2021.109439

Pence VC, Meyer A, Linsky J, Gratzfeld J, Pritchard HW, Westwood M, Bruns EB (2022*b*) Defining exceptional species – a conceptual framework to expand and advance ex situ conservation of plant diversity beyond conventional seed banking. *Biological Conservation* **266**, 109440. doi:10.1016/j.biocon.2021.109440

Raneng J, Pickering C (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Ripple WJ, Wolf C, Newsome TM, Barnard P, Moomaw WR (2020) World scientists' warning of a climate emergency. *BioScience* **70**(1), 8–12. doi:10.1093/biosci/biz088

Rosbakh S, Fernández-Pascual E, Mondoni A, Onipchenko V (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Ruiz Talonia L (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Saatkamp A, Cochrane A, Commander L, Guja LK, Jimenez-Alfaro B, Larson J, Nicotra A, Poschlod P, Silveira FAO, Cross AT, Dalziell EL, Dickie J, Erickson TE, Fidelis A, Fuchs A, Golos PJ, Hope M, Lewandrowski W, Merritt DJ, Miller BP, Miller RG, Offord CA, Ooi MKJ, Satyanti A, Sommerville KD, Tangney R, Tomlinson S, Turner S, Walck JL (2019) A research agenda for seed-trait functional ecology. *New Phytologist* **221**, 1764–1775. doi:10.1111/nph.15502

Sauer C (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Schmidt-Lebuhn A (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Schmitz S, Barrios R, Dempewolf H, Guarino L, Lusty C, Muir J (2023) Crop diversity, its conservation and use for better food systems. In 'Science and innovations for food systems transformation'. (Eds J von Braun, K Afsana, LO Fresco, MHA Hassan) pp. 545–552. (Springer: Cham, Switzerland) doi:10.48565/scfss2021-j983

Schultz N, Duncan C, Good M, Lewandrowski W, Cook S (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

So T, Jalonen R (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Sommerville KD, Newby Z-J, Martyn Yenson AJ, Offord CA (2023) Are orthodox Australian rainforest seeds short-lived in storage? *Australian Journal of Botany* **71**(7), 340–352. doi:10.1071/BT22104

van der Merwe MM, Bragg JG, Dimon R, Fahey PS, Hogbin PM, Lu-Irving P, Mertin AA, Rossetto M, Wilson TC, Yap J-YS (2023) Maintaining separate maternal lines increases the value and applications of seed collections. *Australian Journal of Botany* **71**(7), 406–419. doi:10.1071/BT22136

Walters C, Pence VC (2021) The unique role of seed banking and cryobiotechnologies in plant conservation. *Plants, People, Planet* **3**, 83–91. doi:10.1002/ppp3.10121

Westengen OT, Jeppson S, Guarino L (2013) Global ex-situ crop diversity conservation and the Svalbard global seed vault: assessing the current status. *PLoS ONE* **8**, e64146. doi:10.1371/journal.pone.0064146

Westengen OT, Lusty C, Yazbek M, *et al.* (2020) Safeguarding a global seed heritage from Syria to Svalbard. *Nature Plants* **6**, 1311–1317. doi:10.1038/s41477-020-00802-z

Westwood M, Cavender N, Meyer A, Smith P (2021) Botanic garden solutions to the plant extinction crisis. *Plants, People, Planet* **3**, 22–32. doi:10.1002/ppp3.10134

World Economic Forum (2020) The global risks report. World Economic Forum, Geneva, Switzerland.

Wrigley D (2021) 'Australasian seed science conference: linking seeds with needs; securing our future in a changing world.' Program Booklet. (Australian Seed Bank Partnership: Canberra, ACT) Available at https://www.seedpartnership.org.au/wp-content/uploads/2021/10/ASSC-2021-Program-Booklet.pdf [accessed 22 August 2023]

Wrigley D, Desmond B (2023) Australian seed bank partnership: strategic plan 2023-30. (The Australian Seed Bank Partnership: Canberra, ACT, Australia) https://www.seedpartnership.org.au/wp-content/uploads/2023/02/ASBP_Strategic_Plan_2023-30_FINAL.pdf [accessed 22 August 2023]

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