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Novel and emerging seed science research from early to middle career researchers at the Australasian Seed Science Conference, 2021

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ABSTRACT

Seed science is a vital field of research that contributes to many areas of knowledge in fundamental ecology and evolution, as well as in applied areas of food production, and the conservation and restoration of native plants. A large amount of novel information, technologies and processes in seed science research are being produced and developed by early to middle career researchers (EMCRs) in academic, government and private science sectors. This breadth and novelty of research by EMCRs was evident at the second Australasian Seed Science Conference held online in September 2021. EMCRs represented almost one-third of the presenting delegates at the conference and covered research in areas including functional seed trait relationships, responses of seed traits and germination to environmental change, managing seeds in *ex-situ* seed and germplasm collections and using seeds as food sources. As future environmental, social and economic challenges arise, EMCR seed scientists will be at the forefront of emerging fundamental ecological and evolutionary seed science knowledge, as well as the development of technologies and processes for the conservation of native species, the utilisation of seeds in agriculture and food production, and many new ideas yet to be discovered.

Keywords: climate change ecology, germination, germplasm conservation, global food security, plant conservation, plant restoration, plant functional traits, seed ecology, seed sources, seed storage.

Introduction

Seeds are a key stage of the plant lifecycle and play a critical role in determining population survival and adaptation to environmental change (Fenner and Thompson 2005; Long *et al.* 2015; Postma and Ågren 2016). Despite the importance of seeds to plant population dynamics, studies on mature plant life stages are often prioritised in vegetation research (Gioria *et al.* 2014; Chick *et al.* 2016). Seeds are the major currency for safeguarding global food stores (Colville and Pritchard 2019; FAO 2019) and restoring vegetation in degraded landscapes (Merritt and Dixon 2011; Dalziell *et al.* 2022). Therefore, a major challenge in the coming decades is to understand the variation in seed function, seed tolerance under a range of environmental conditions, the evolution of early life history traits, and the changing role of seeds in culture and society.

Seed research across individual-, community-, and societal-level scales is necessary to respond to existing and developing environmental challenges. At an individual level, seed characteristics indicate a species' ability to tolerate a range of environmental conditions and their potential for storage and preservation, which is critical knowledge for the future of agriculture and biodiversity (Martínez-Andújar *et al.* 2012; Cochrane *et al.* 2015; Jiménez-Alfaro *et al.* 2016; Saatkamp *et al.* 2019). At a community level, studying seeds reveals 'a memory of past and present' (Gioria and Pyšek 2016), such as legacy effects of previous environmental conditions, indications of future stand composition, and the first signs of invasion from introduced species (Amiaud and Touzard 2004; Gioria *et al.* 2014; Gioria and Pyšek 2016; Harris *et al.* 2021). At a cultural level, seeds can reveal culinary, decorative and mercantile traditions from cultures across the globe and throughout history (Müller 2014; Bouchaud *et al.* 2015). The scientific study of seeds across agriculture, ecology, evolutionary biology, conservation and restoration, anthropology and archaeology, comprises a growing field of research that will become increasingly pertinent in future research under continuing global changes (Ooi 2012; Havens *et al.* 2015; Hampton *et al.* 2016).

Early to middle career researchers (EMCRs) comprise a large proportion of scientists driving research and innovation in seed science across numerous scales and are important future leaders of research in this field. Twenty-four EMCR presenters were amongst the attendees at the recent Australasian Seed Science Conference (ASSC) held online in September 2021, emulating the breadth and novelty of research in the seed science field, and accounting for approximately 30% of total presenting delegates. These EMCRs represented a diverse range of government, academic and industry organisations from five countries, including Australia, Indonesia, Switzerland, the United States of America (Hawai'i) and the United Kingdom (Fig. 1). A targeted social event for EMCRs brought these researchers together and led to the discussion of research, career development, and common experiences and challenges for EMCRs in the seed science sector. Collectively, EMCRs gained a sense of collegiality within the seed science community and a collective sense of shared research interests, whilst progressing ideas related to seed science.

Breadth and novelty of research presented by early to middle career researchers at the Australasian Seed Science Conference 2021

The overarching conference theme 'Linking seeds with needs: securing our future in a changing world' for ASSC 2021 was exemplified through research presented by EMCRs, including topics from fundamental biology to practical applications of seeds in society. In total, EMCRs presented 20 scientific talks and four posters, showcasing cutting-edge research covering the four main conference themes: (1) *Seed Biology and Evolutionary Ecology*, (2) *Seed Sourcing and End-use*, (3) *Seed and Genebank Management*, and (4) *Seeds in Culture and Society*.

Collectively, EMCRs presented research on seed science for over 2000 species across the globe. Of these species, 479 were Australian native plants, and of these Australian plants, 19 species were listed as threatened, vulnerable or endangered species at the time of the conference (See Supplementary material Table S1 for full data on EMCR research presented at ASSC 2021). Key themes that emerged from EMCR research included the study of seed functional traits, seed responses and adaptations to environmental change, applications of seeds and *ex-situ* seed banks to the conservation and restoration of species, and the use of seeds as food. Taken together, EMCRs delivered research that responded to the needs for securing our future in a changing world.

Seed traits and functioning

A key aspect of seed biology and ecology that emerged from research presented by EMCRs included seed functional traits, their biological scaling and how increased data and knowledge of seed traits may contribute to the conservation of plant species. Dr Si-Chong Chen (invited international keynote speaker – Seed Biology and Evolutionary Ecology theme), presented fundamental research on biomass allocation across seed functional components at various ecological scales from the individual level to global-scale patterns (Chen and Giladi 2018; Chen *et al.* 2019, 2020). Her findings highlighted the strong correlations between functional components of seeds and improved our understanding of plant reproductive strategies. Chen emphasised that a seed consists of several functional components, such as seed coat and seed reserve, rather than existing as an integrated unit of evolutionary characteristics. The absolute mass and relative proportion of a seed influences a suite of processes, from seed development to seedling establishment. Rocco Notarnicola exhibited a study that tested the commonly assumed trade-off between seed size and seed number (whereby species tend to invest either in larger seeds that are lower in total number per canopy square metrer per year; or in smaller seeds that are higher in number per canopy square metre per year; Moles and Westoby 2006) in the Australian alpine herb (*Wahlenbergia ceracea*). Interestingly, Notarnicola found contrasting results to previous assumptions; there was only weak evidence for seed size – seed number trade-offs under warmer temperatures. Although warming led to the production of more flowers (in concurrence with the life history strategy of a seed size–seed number trade-off), higher temperatures led to many aborted flowers and reduced seed production, which left many seeds empty or immature. The research presented by Dr Chen and Mr Notarniacola, on the relationships between seeds' functional characteristics, will progress foundational theories of seed science and equip conservationists to best protect plant species now and into the future.

Seed traits that describe physiological thresholds to temperature and moisture are critical for defining seasonal windows for seed germination (Saatkamp *et al.* 2019). Particularly in water-limited ecosystems where precipitation events are infrequent and unpredictable, or in habitats that experience fire, understanding how seeds respond to moisture pulses can be critical for both conservation and restoration initiatives. Under this premise, Dr Wolfgang

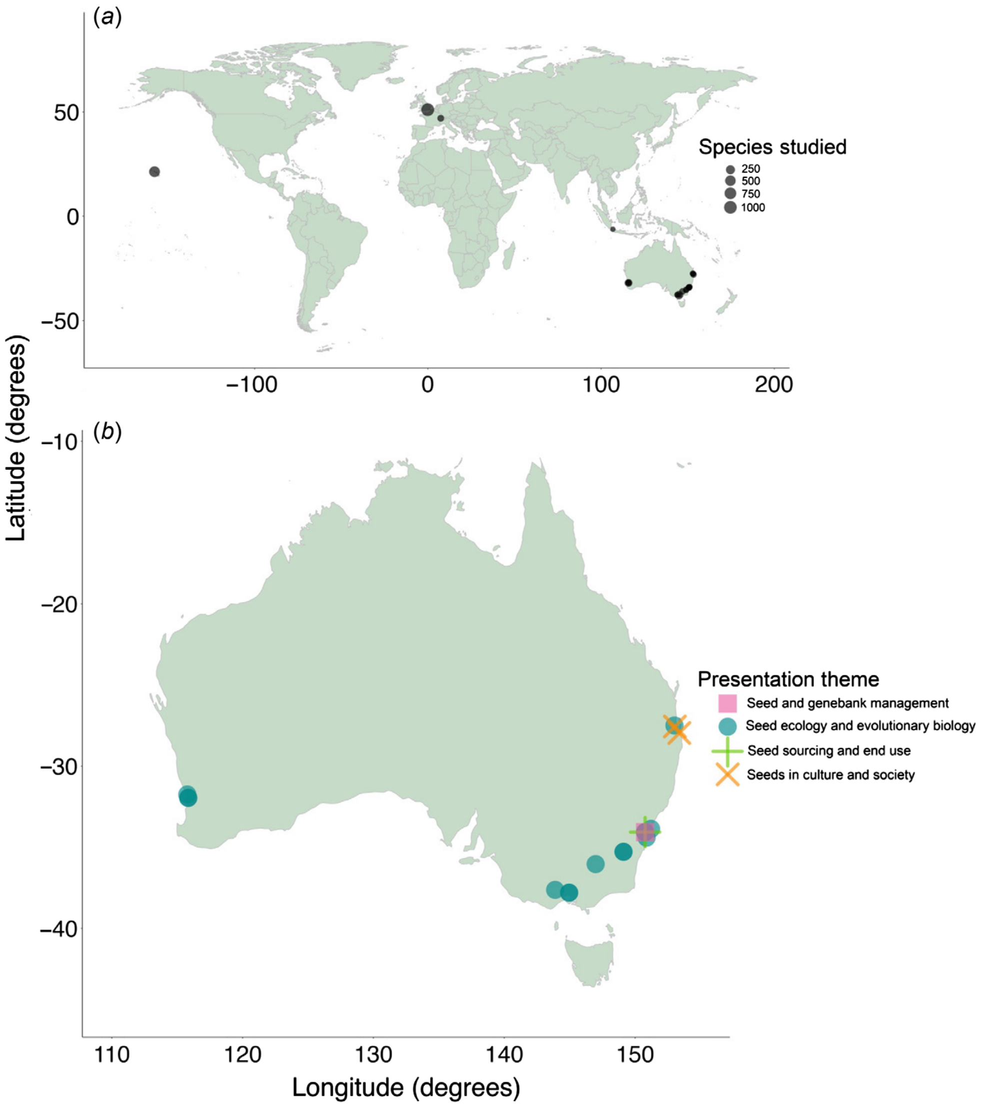

Fig. 1. (*a*) Locations of global EMCR presenters at the ASSC 2021 conference with point size showing number of species studied per presentation; (*b*) Locations of Australian EMCR presenters at the ASSC 2021 conference with shape and colour of point showing theme of each presentation. All locations are the addresses specified by the delegates as of the time of delivering their presentation at ASSC 2021 and include both oral and poster presentations. These can be found in Supplementary material Table S1.

Lewandrowski focused his presentation on hydrothermal germination requirements in threatened, narrow-range endemics and widely distributed plant species that co-occur on water-limited, rocky banded ironstone landscapes from the Goldfields in Western Australia. His research indicated that narrow-range endemic species had slower germination speeds, and cool and wetter hydrothermal thresholds for germination compared to generalist species that were often quicker to germinate and had wider thermal ranges for germination. Dr Emma Dalziell presented novel research on the allometric patterns of metabolic rates in seeds using a recently developed fluorescence-based closed-system respiratory method and analysis (Tomlinson *et al.* 2018). This work showed that seed mass is significantly correlated with seed metabolic rate; a pattern that has been found before in animal and whole-plant studies, and is newly confirmed in seeds through her research. Dalziell's research also uncovered statistically similar seed metabolic rates between related taxa. Domesticated crop species typically had higher seed metabolic rates, most likely due to selective breeding, leading to the production of rapid development and growth traits in these species and an increased seed metabolic rate. Dr Lewandroswki and Dr Dalziell's presentations progressed knowledge on seed growth and development that is fundamental to refining how species are germinated and utilised for conservation, restoration and agricultural purposes.

EMCRs in seed science research are determining and quantifying fundamental patterns in seed functional, morphological and physiological traits across broad biogeographical gradients and within taxonomic parameters. Not only do these studies progress fundamental knowledge, they also enable researchers to determine generalised patterns in the seed life stage, enabling predictions of how species will respond to their environment in the future. Generalisable quantifications of seed traits have important implications in seed conservation and *ex-situ* seed storage, as they elucidate seed longevity and resulting storage requirements, fundamental to preserving viable collections of plant materials many decades into the future (Merritt *et al.* 2014; Colville and Pritchard 2019).

Seed science and environmental change

As well as covering the fundamental and applied questions of seed traits and their relationships with environmental and abiotic gradients, many EMCRs presented research on seeds and their responses and relationships with environmental change, particularly climate change. Climate change is a highly pertinent topic in biology, ecology and evolution (Parmesan 2006; Lavergne *et al.* 2010) with the potential to have substantial impacts on biodiversity and human welfare. The seed science sector is at the forefront of determining the impacts of climate change on early plant life stages and therefore species' entire life cycles (Walck *et al.* 2011; Ooi 2012; Everingham *et al.* 2021). Determining the responses and adaptations of seed functioning, traits and physiology to climate change was a well-represented topic by EMCRs at ASSC 2021. Dr Susan Everingham (winner of the EMCR prize for best oral presentation) demonstrated an emerging method in seed-based evolutionary ecology that leverages historic seed collections in *ex-situ* seed banks, to determine seed and seedling trait changes through time. Everingham analysed whether these changes in Australian plants were significantly related to changes in climate metrics, such as mean temperature/precipitation and extremes in climate. Everingham's research found that seed traits, including seed shape, seed viability and germination rate are already responding to recent anthropogenic climate change pressures. As temperature variability increased in regions across Australia, seed viability and germination success increased, whereas, in regions in Australia where dry spell durations have increased through time, seed viability has decreased and seeds have become longer and flatter in their shape (Everingham *et al.* 2021). This work highlights that seeds are a vital life stage in determining the ability of plants to adapt to future increases in temperature and/or extreme climatic events (Everingham *et al.* 2021).

EMCRs also presented cutting-edge research that leveraged seeds to predict the future impacts of climate change on plants and thus mitigate species losses under extreme temperature increases and precipitation reductions. Increased temperature, decreased precipitation and more frequent and prolonged drought will continue to intensify in the Australasian region in the coming decades (Domingues *et al.* 2020; Kirono *et al.* 2020) and knowledge of seed responses to these changes is vital for the protection of plant species and ecosystems. EMCRs Dr Justin Collette and Dr Nathan Emery demonstrated a novel methodology and associated open-access analytical R code they developed for testing germination responses to current temperatures and future predicted temperatures on thermogradient plates (Collette *et al.* 2022). Using this method, Dr Emery determined that while some woody species in threatened ecological communities in Northern New South Wales may have successful germination under future temperatures, some dry rainforest species were predicted to have significantly reduced germination under climate-change-driven temperature increases. Dr Nick Schultz presented complementary work led by Dr Corrine Duncan that distinguished germination strategies in Australian seeds (Duncan *et al.* 2019). By manipulating both temperature and moisture availability, Dr Duncan determined that some arid Australian species were risk-takers in their germination strategy, requiring less water to germinate even under increased temperatures, and other species were risk-avoiders, requiring both high moisture and low temperatures to germinate (Duncan *et al.* 2019). The results imply that using tube stock may be more successful than using seed when restoring risk-avoider species in arid zone vegetation, due to the difficulty of meeting the germination requirements of risk-avoider species in the field. These studies provide essential information on how climate change may influence germination, integral to adapting restoration efforts to this emerging environmental challenge.

EMCRs also investigated the influence of other environmental drivers within seed science. Ella Plumanns-Pouton (winner of the EMCR best speed talk) presented methods and early preliminary results for a multi-year study investigating how variation in fire history influences the diversity of the soil seedbank in temperate heathlands. The work investigates how a combination of the time since the last fire, the interval between fires, and the severity of the last fire determine species richness, species occurrence and relative abundance within sites. Similarly, Amy Buckner (winner of the EMCR poster prize) introduced a study investigating the importance of fire for stimulating germination in Australian Alpine ecosystems. Buckner found that soil seedbanks from recently burnt alpine sites produced a lower diversity of germinated seedlings and found no heat and smoke treatment effects on germination proportions. Although fire is an essential environmental cue in many Australian ecosystems, very few alpine plants demonstrated improved germination responses after exposure to fire. As fire frequency is predicted to increase across Australian Alpine regions, alpine species may be at risk if maladapted to fire cues. These studies advance knowledge on how fire influences Australian seed composition and germination responses, essential to managing fire to best protect ecosystems, now and in the future.

Seeds, seedbanks and genebanks in plant conservation and restoration

Not only are early to mid-career seed scientists innovatively researching fundamental ecology and evolution, they are also at the forefront of using seeds in conservation and restoration. This aspect of EMCR seed science was covered by topics presented at ASSC 2021, including the importance of seed microbiomes in wild seeds and natural seedbanks, as well as the storage and management of seeds in *ex-situ* seed banks and genebanks.

Two EMCRs from the Australian Institute of Botanical Science – Allison Mertin (working in conjunction with the University of Melbourne) and Merize van der Merwe (working in conjunction with the University of Wollongong) showcased innovative research on seed fungal endophytes (the fungi present inside the tissue of seeds) and demonstrated the large knowledge gap on the factors that influence seed fungal endophytic diversity. Both researchers used lab culturing techniques, morphological analyses and Sanger sequencing to determine the seed endophytic community inside *Banksia serrata*, *Banksia ericifolia*, *Themeda triandra* and *Microlaena stipoides* seeds from multiple populations in differing locations. They discovered that seed endophytic composition and diversity can vary widely within species across sites and across species within a single location. Seed endophytic communities can also show large changes over time within a single host species in one location. Restoration of plant communities using sown seeds typically focuses on soil microbial knowledge and soil microbial priming of the seeds. However, Mertin and van der Merwe propose that it is vital to consider both the soil microbial and the seed microbial community in plant restoration to achieve the greatest success in seed germination and seedling establishment in restored populations in natural and urban environments.

Ex-situ seed- and genebanks are critical for the preservation of wild and agricultural plants through seed storage and tissue storage; particularly in threatened, endangered and, in some cases, extinct species (Offord and Meagher 2009). Seed- and genebanks ensure that stored plant material can be used in the conservation, restoration or translocation of species across Australia, now and into the future. Rainforest species are frequently overlooked in seed- and genebank storage as they have recalcitrant seeds (seeds that don't survive the drying and freezing processes that are common practice in seed bank management). However, rainforest species are part of an important Australian habitat type that requires conservation management. Fortunately, the early career researchers from the PlantBank at the Australian Institute of Botanical science are providing exciting new research in these systems. Dr Zoe-Joy Newby spoke at ASSC 2021 on the longevity of Australian rainforest seeds in *ex-situ* seed bank storage conditions. As shown in the paper in this Special Issue by Sommerville *et al.* (2023), the average longevity in the storage of 26 rainforest seeds was only approximately 18 days, highlighting the need for regular rainforest seed collection and preservation using other methods such as cryopreservation (a technique of plant tissue storage). In a complementary study, EMCR Lyndle Hardstaff, another researcher at the PlantBank and working in conjunction with Curtin University, Western Australia, led research into the storage and preservation of Myrtaceae species using cryopreservation. Hardstaff found that some seeds of *Backhousia* and *Syzygium* species were able to survive liquid nitrogen treatment for cryostorage. However, many species' seeds did not survive or grow after liquid nitrogen treatment, suggesting cryodamage from insufficient desiccation. They also noted that shoot tips rather than seeds may be a more appropriate material to use in cryostorage for species with high rates of contamination *in vitro*. These presentations showcase work that improves storage techniques for Australian seeds, critical to safeguarding global food stores and species for restoration efforts.

Seed storage in *ex-situ* seed- and genebanks is the initial step of conservation for many species, however, ensuring these species have the ability to germinate after storage periods is the next crucial step in the germplasm conservation process. Seed germination success is required if seeds are to be utilised for the long-term conservation of species and in future restoration or translocation efforts. Dr Ganesha Liyanage works closely with Australian rainforest species in the *Acronychia* genus to determine the dormancy-breaking requirements in these unorthodox, hard-to-germinate seeds. Dr Liyanage found that some *Acronychia* species required scarification near the radicle emergence point to initiate germination (Liyanage *et al.* 2020). The method may also be a suitable dormancy-breaking technique for future stored species in the genus.

Looking toward the future of seed banks and germplasm conservation was also covered by EMCRs at the conference. Nathaniel Kingsley from the Lyon Arboretum, Hawai'i, introduced a new procedure for digitising the seed collection of Hawai'ian flora using multilayered, Z-stacking imaging technology, which allows the capturing of the entire three-dimensional seed in focus. These images are then available to researchers to determine seed size and mass, as well as for plant and seed identification in further collections (Miller *et al.* 2018). Early to middle career researchers are at the forefront of new research and developing technology that will enhance the management of seeds and germplasm in *ex-situ* seed and genebanks. These tools and research generated by EMCRs today will be invaluable in plant conservation, agriculture and food production in the future.

Seeds in culture and society

A new theme in the conference this year, *Seeds in Culture and Society*, provided a novel perspective on the broader use of seeds beyond scientific institutions to wider society in developing industries and applications such as food security, community gardens and local-scale revegetation of native habitats. The theme of seeds in culture and society also highlighted the importance of collaboration and partnership between scientists and First Nations communities (particularly, the importance of intellectual property rights for Indigenous groups and legal frameworks that ensure these entitlements), local communities and other key industries/ societal groups. This theme featured research from Sera Susan Jacob, a PhD candidate from the ARC Centre for Uniquely Australian Food at The University of Queensland. Jacob's research focuses on exploring the potential of wattleseeds for food applications in modern diets. Wattle seeds are rich in dietary fibre, protein and many essential micronutrients, and have been an essential part of the diets of many Aboriginal communities across Australia. Jacob has found many structural and nutritional differences between different varieties of wattleseeds, making them comparable to common legumes and beans. With the growing interest for Australian native wattleseeds in Australia's food market, she is hopeful that findings from her work will open avenues where wattleseeds can be consumed much like other legumes in the same family and not just as a flavouring ingredient. Within the same theme of the conference, Jesse Raneng, a PhD candidate from Griffith University, shared research on the increased number of community gardens and plant diversity within these gardens, in the region of Brisbane, Australia. Community gardens are an excellent resource for local community seed collection and seed/seedling exchange. However, Raneng showed that there is a large gap in the literature for assessing the potential of these gardens to contribute seeds for agro-biodiversity and food security. These EMCRs and others leading this field will continue to forge important connections and collaborations between science and society to ensure seeds can be utilised for the preservation of native vegetation, increased food security, and cultural connections to natural space.

Frontiers in seed science research techniques used by early to middle career researchers

Given the breadth of research highlighted by seed science EMCRs at ASSC 2021, we posit that EMCRs are an essential pillar to the development of creative and resourceful solutions to address current and future seed science challenges. For example, by measuring allometric patterns in seed respiration, research from Dr Dalziell can further enhance our capacity to understand and predict seed longevity and viability. Using hydrothermal studies to quantify environmental thresholds or developing statistical approaches to quantify thermal niches for germination under current and future climate scenarios, the research by Dr Lewandrowski and by Dr Collette provides an insight, as well as predictive methodologies, to understand species responses to global climate change impacts. Additionally, our ability to characterise, describe and conduct morphological assessments on seeds is significantly enhanced through the approach provided by Nathan Kingsley. Broadly, these technologies not only help to accelerate the acquisition and application of information across the seed sciences, but most importantly, demonstrate alternative perspectives to solve emerging research questions and problems.

In addition, the innovative techniques and analyses generated by EMCRs at the seed science conference may play a critical role in global initiatives relating to the UN Decade of Restoration (https://www.decadeonrestoration.org/about-un-decade), and in solving the global food crisis. The UN Decade of Restoration aims to restore degraded and deforested lands, which will require the use of high-quality seeds, for which seed storage, seed dormancy and environmental conditions to support germination of many species remain unresolved (Sommerville *et al.* 2021; Collette *et al.* 2022; Dalziell *et al.* 2022). Similarly, the global food crisis requires an understanding into best-practice seed processing and storage methodologies; generating seeds that are climate resilient; and producing high crop productivity and yield to improve food security (Dalziell and Tomlinson 2017; De Vitis *et al.* 2020; Leger *et al.* 2021). Techniques in seed collection, seed storage and seed germination developed by EMCRs will be at the forefront of solving these global issues and promoting large-scale restoration.

Furthermore, our natural ecosystems are facing many threats, particularly in the Australasian region, from disease, climate change and land degradation. Fungal pathogens including myrtle rust (caused by *Austropuccinia psidii*), are posing large risks and threats to native species. In relation to these threats, optimal banking/cryopreservation procedures developed by EMCRs such as Lyndle Hardstaff may be the only way to save keystone as well as threatened plant species from the brink of extinction (Hardstaff *et al.* 2022). Climate change remains one of our most significant challenges to date, therefore knowledge and novel analyses of wild species' adaptations in seed traits in the past, may help us predict their adaptive capacity in the future (Ooi 2012; Everingham *et al.* 2021). Many projects that use seeds to further conservation, or restoration of degraded land, will require testing in the field. New data and techniques developed by EMCRs will be critical in understanding the regenerative capacity of particular seeds following disturbance and will provide key mechanistic insights into recruitment bottlenecks between seeds and established plants (e.g. Liyanage *et al.* 2016; Hodges *et al.* 2019; Tangney *et al.* 2020; Miller *et al.* 2021).

Conclusion

Early to middle career researchers are fundamental to the progression of novel seed science research. Their work is essential to meeting the needs of current and future environmental, social and economic challenges. EMCR seed scientists are progressing foundational ecological and evolutionary knowledge, as well as the development of technologies and processes that are integral to the conservation of native species and the utilisation of seeds in agriculture and food production. EMCR research represents the forefront of new ideas pertaining to understanding seed functional traits, seed responses and adaptations to environmental change, applications of seeds and *ex-situ* seed banks to the conservation and restoration of species, and the use of seeds in society. Research contributed by EMCRs at the Australasian Seed Science Conference represented over 2000 plant species, demonstrating a wide reach across geographic scales and taxonomic groups. EMCRs showcased innovative methodologies, including creative germination methods, new analysis techniques and openly available scripts, essential to collectively progressing seed science. Furthermore, EMCRs took seed research in new directions, beyond science, to *Seeds in Culture and Society* stream of the conference. The research presented by EMCRs at the Australasian Seed Science Conference 2021 demonstrates the capacity and importance of EMCRs in progressing new frontiers of seed science in Australasia and globally. Furthermore, it highlights the capability of current EMCRs to imminently lead and influence the next generation of EMCRs, to develop their own critical scientific developments in the face of new global challenges.

Supplementary material

Supplementary material is available online.

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Data availability. Data associated with this manuscript are available in Supplementary Table S1, code for the creation of Fig. 1 is freely available at https://github.com/SEveringham/AustralasianSeedScienceConference2021.

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