CSIRO PUBLISHING
Wildlife Research, 2021, **48**, 289–303
https://doi.org/10.1071/WR20154

Review

An overview of the history, current contributions and future outlook of iNaturalist in Australia

Thomas Mesaglio [A,C] *and Corey T. Callaghan* [A,B]

[A]Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, The University of New South Wales, UNSW Sydney, NSW 2052, Australia.
[B]Evolution & Ecology Research Centre, School of Biological, Earth and Environmental Sciences, The University of New South Wales, UNSW Sydney, NSW 2052, Australia.
[C]Corresponding author. Email: thomasmesaglio@gmail.com

Abstract. Citizen science initiatives and the data they produce are increasingly common in ecology, conservation and biodiversity monitoring. Although the quality of citizen science data has historically been questioned, biases can be detected and corrected for, allowing these data to become comparable in quality to professionally collected data. Consequently, citizen science is increasingly being integrated with professional science, allowing the collection of data at unprecedented spatial and temporal scales. iNaturalist is one of the most popular biodiversity citizen science platforms globally, with more than 1.4 million users having contributed over 54 million observations. Australia is the top contributing nation in the southern hemisphere, and in the top four contributing nations globally, with over 1.6 million observations of over 36 000 identified species contributed by almost 27 000 users. Despite the platform's success, there are few holistic syntheses of contributions to iNaturalist, especially for Australia. Here, we outline the history of iNaturalist from an Australian perspective, and summarise, taxonomically, temporally and spatially, Australian biodiversity data contributed to the platform. We conclude by discussing important future directions to maximise the usefulness of these data for ecological research, conservation and policy.

Keywords: citizen science, iNaturalist, biodiversity data, conservation, community science.

Received 3 September 2020, accepted 16 January 2021, published online 19 March 2021

Introduction

Citizen science, or community science – the cooperation between volunteers and professional scientists – is increasingly leveraged in the fields of ecology and conservation. Citizen science initiatives, and their associated data, are increasing at exponential rates (Pocock *et al.* 2017). As a result, biodiversity research is increasingly reliant on citizen science data to understand ecological patterns at spatial and temporal scales not possible mere decades ago. Concomitantly, there is an increasing reliance on the use of citizen science data for conservation planning and monitoring (Chandler *et al.* 2017; McKinley *et al.* 2017; Young *et al.* 2019). But despite the prevalence of citizen science data, there are still several barriers to its use as a primary research tool (Burgess *et al.* 2017).

A major reason for the reluctance towards using citizen science data is questions surrounding data quality, such as misidentifications or underlying biases skewing the data. Yet, recent work has highlighted that the accuracy of citizen science data is increasingly comparable to that collected by experts (Aceves-Bueno *et al.* 2017). An examination by external experts of 3287 records (2234 plants, 1053 moths) submitted to the platform iSpot (www.ispotnature.org) verified more than 92% of these as accurately identified by citizen scientists (Silvertown *et al.* 2015). Further, because the quantity of data collected by citizen scientists is so great, there are several statistical techniques that can be used to identify and account for the noise and bias in citizen science initiatives (Bird *et al.* 2014), ranging from hierarchical modelling using random effects to account for inherent noise (Isaac *et al.* 2014), to spatial and temporal subsampling to minimise biases (Wiggins *et al.* 2011), to integrating professionally collected data with opportunistically collected data (Fithian *et al.* 2015; Pacifici *et al.* 2017). Statistical techniques are increasingly being developed, which will continue to increase the utility of citizen science data for biodiversity and ecological research.

Citizen science initiatives generally range from structured (e.g. rigorous protocols, training, predetermined time and location of surveys, collection of effort information) to unstructured (e.g. no training necessary, opportunistic in nature, data collected at any time or place), and each of these has trade-offs. For example, structured initiatives are likely to collect data with less bias, but the quantity of data is often greater from unstructured initiatives with little to no formal protocols. Citizen science initiatives also vary in their approach, including contributory/

participatory (i.e. participants engage in a project developed by professionals), or collaborative (i.e. participants are involved in defining the scope, purpose, and methodology) approaches (Danielsen *et al.* 2005; Pocock *et al.* 2019).

Of all citizen science initiatives, iNaturalist (www.inaturalist.org) is one of the most globally successful on the basis of participation and quantity of data collected. iNaturalist is a multi-taxa citizen science platform hosted by the California Academy of Sciences and National Geographic Society. Its primary goal is to connect people to nature, while also aiming to generate scientifically valuable biodiversity data. iNaturalist is an unstructured citizen science initiative that is opportunistic in nature, allowing participants to contribute observations (e.g. photos, sound recordings) of any living organism, or traces thereof, with associated spatiotemporal coordinates. Records are then identified to the lowest possible taxonomic resolution by other iNaturalist users. Data are presence-only, such as those data from iSpot or FrogID; conversely, citizen science initiatives such as eBird or Reef Life Survey involve the collection of species lists, allowing for easy inference of absences. An observation is deemed 'Research Grade' when it has two or more suggested identifications and more than two-thirds of these identifications agree. Although 'Needs ID' observations are not necessarily less taxonomically accurate than Research Grade observations (Hochmair *et al.* 2020), designation as Research Grade allows these records to be automatically exported to the Global Biodiversity Information Facility (GBIF; provided the observation is published under a CC0, CC BY, or CC BY-NC license). Australian observations (both Research Grade and Needs ID) are also automatically exported to the Atlas of Living Australia (ALA; provided the observation is shareable under a Creative Commons license). Importantly, any subsequent changes to these observations in iNaturalist, such as changed identifications, are also reflected in GBIF and the ALA.

Since the launch of iNaturalist in 2008, it has seen immense uptake on a global scale, with >54 million observations of ~306 000 identified species, contributed by >1.4 million observers and spanning 252 countries and territories. The data from iNaturalist have already made significant impacts in ecological and biodiversity research, and have been validated in their use for vegetation mapping, albeit at a small scale (Uyeda *et al.* 2020). More broadly, data from iNaturalist have been used to detect range extensions of alien species (Agarwal 2017; Vásquez-Restrepo and Lapwong 2018), quantify urban tolerance of organisms (Callaghan *et al.* 2020*a*), map character traits such as wing phenotypes and colour morphs (Drury *et al.* 2019; Lehtinen *et al.* 2020), and record the rediscovery of lost species (Jain *et al.* 2019; Richart *et al.* 2019).

Surprisingly, syntheses highlighting the advances of our knowledge as a result of iNaturalist are rare, with many papers instead focusing on singular records of interesting and unique data points (e.g. Fig. 1). Yet, such syntheses are important to (1) inform the scientific community of the value of the data, (2) provide feedback to the citizen science participants (de Vries *et al.* 2019) and iNaturalist staff, and (3) highlight future research questions. Here, we synthesise Australian biodiversity data contributed through the iNaturalist platform. We extracted all georeferenced and dated records of wild organisms from iNaturalist associated with a photograph or sound file (i.e. 'verifiable' observations), and uploaded on or before 21 November 2020 (api.inaturalist.org). We used observations within continental Australia, islands under Australian jurisdiction, and the waters constituting Australia's Exclusive Economic Zone (which extends to a maximum distance of 200 nautical miles). We followed iNaturalist's taxonomy for all taxa. First, we highlight the exponential growth of iNaturalist in Australia, providing a brief history of the platform from an Australian perspective. Second, we provide a taxonomic overview of the biodiversity data, including a summary of endangered and rare species data. Third, we provide a spatial summary of the data, highlighting important spatial gaps in these data. Fourth, we discuss significant projects, highlighting the broad utility and adaptability of the iNaturalist platform for targeted citizen science projects. Last, we conclude with an overview of significant next steps for the future for iNaturalist in Australia that will maximise the information content for researchers aiming to better understand biodiversity research in Australia. Ultimately, we hope that this overview will (1) help to encourage naturalists and professionals alike to become involved with the iNaturalist community in Australia, and (2) stimulate future research directions that will benefit the continuous improvement of iNaturalist as an entity in data collection for biodiversity research.

Temporal summary of Australian iNaturalist data

Current data contributions

As of 21 November 2020, 26 849 users have contributed 1 637 950 verifiable observations (of which 1 036 648 are Research Grade) of 36 391 identified species in Australia, with 11 433 users providing identifications. Although ranked fourth in the world for number of observations, Australia is ranked third for number of species, and second for average number of observations per observer (Table 1). Australian observers follow a strong long-tailed distribution, with the top 10 observers (representing 0.04% of all Australian observers) contributing 20.64% of all Australian observations, confirming the general pattern of 'power users' (Supplementary material Table S1; Wood *et al.* 2011; Rowley *et al.* 2019). The distribution of identifiers follows a similar pattern, with 16.6% of all identifications of Australian observations made by the top 10 users (Table S2).

History of iNaturalist in Australia

Use of iNaturalist in Australia started slowly, with little growth from 2008 to 2015. However, from mid-2016 onward, several events drove dramatic increases in observation rates, the number of observers, and the number of observed species (Fig. 2). First, in 2016, Questagame, a different citizen science biodiversity platform, gave users the option of syncing their account with iNaturalist, helping drive the first significant increase in Australian observation rates. In October 2016, the creation of the *Australasian Fishes* Project (https://www.inaturalist.org/projects/australasian-fishes) sparked a similar acceleration in observation rates. Before *Australasian Fishes*' inception, the most observations uploaded in any given month only just exceeded 2000, and after its inception, observation rates more than tripled compared with the average monthly rate of the preceding year.

From 2016 onwards, observations of Australian taxa have continued to increase at an accelerating rate, with this sustained organic growth occasionally punctuated by increasingly large

The critically endangered red handfish (*Thymichthys politus*) is one of the rarest fishes in the world, with an estimated population size of under 100.

This is the first record of a female angled Australian barkhopper (*Paraselina brunneri*) since its description in 1887, and one of only five records since the holotype was collected.

This record of a Papuan frogmouth (*Podargus papuensis*) is the first ever observation of this species swimming.

This is both the only known photograph and only known georeferenced record anywhere of *Clunio pacificus*, a species of non-biting midge.

Fig. 1. Examples of Australian observations of extremely rare species and behaviours. (*a*) Phil Malin (@acanthaster); (*b*) Nick Lambert (@nicklambert); (*c*) David White (@davidgwhite); Thomas Mesaglio (@thebeachcomber).

Table 1. Observation statistics for the top 6 contributing countries to iNaturalist

Country	Observations	Species	Observers	Identifiers	Average number of observations per observer
USA	28 622 336	75 352	776 694	104 701	36.85
Canada	4 076 115	27 654	97 475	27 083	41.82
Mexico	2 508 219	36 813	57 204	19 925	43.85
Australia	1 637 950	36 391	26 849	11 433	61.01
United Kingdom	1 277 446	14 879	53 470	12 909	23.89
South Africa	1 093 082	28 703	11 889	7253	91.94

spikes driven by external events. The first of these major spikes occurred in May 2019 with the closure of BowerBird. Hosted by Museums Victoria, BowerBird was Australia's core biodiversity citizen science platform. With a particularly strong focus on invertebrates, BowerBird users tracked large range expansions for invasive species (Baumann *et al.* 2016), rediscovered species assumed to be extinct (Richter 2015) and recorded undescribed species (Walker 2014). Over 70 000 records were migrated to iNaturalist from BowerBird, a merger that also attracted new users from BowerBird, helping further accelerate observation rates over time for the iNaturalist platform.

In May 2019, the Atlas of Living Australia (ALA) began collaborating with iNaturalist by forming iNaturalist Australia, a local node of the broader iNaturalist platform. This collaboration has allowed the ALA to access the strong network of identifiers provided by iNaturalist, while also prompting more Australian experts to join iNaturalist. In 2020, Australia participated in the City Nature Challenge (CNC; https://citynature-challenge.org/) for the first time, with four cities, namely, Sydney, Adelaide, Geelong and Redland City, officially competing, and the rest of Australia being encouraged to also submit as many records as possible from 24 to 27 April. In just 4 days,

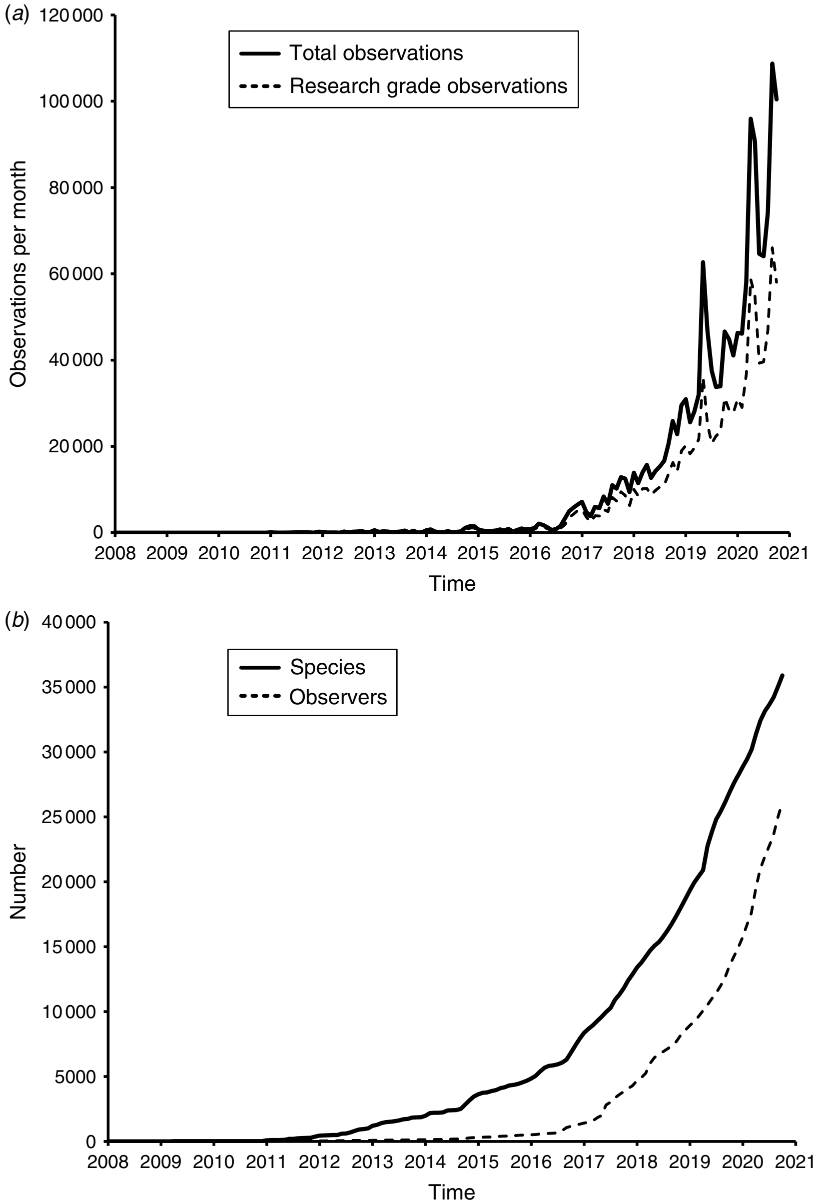

Fig. 2. Growth of Australian iNaturalist involvement over time. (*a*) Number of total observations and research grade observations uploaded per month. An observation is deemed 'research grade' when it has two or more suggested identifications and more than two-thirds of these identifications agree. (*b*) Cumulative number of observers and observed species.

1476 Australian users, many of whom were new users recruited to iNaturalist through CNC advertising, submitted 24 881 observations of 4724 identified species. In May 2020, NatureShare (Victoria's main biodiversity citizen science platform) closed down and its records were migrated across to iNaturalist. As with BowerBird, this process generated new iNaturalist observations and attracted new users.

After the successes of the CNC, the Australian organisers coordinated the Great Southern BioBlitz (https://greatsouthern-biobl.wixsite.com/website) to promote observations during the southern hemisphere spring. With 1446 observers uploading 32 213 observations of 5101 identified species from 25 to 28 September as part of the event, Australian uploads exceeded 100 000 in a single month for the first time.

Taxonomic summary of Australian iNaturalist data

Animals are the most observed kingdom in Australia on iNaturalist (68%), followed by plants (25%) and fungi (6.5%), with all other kingdoms constituting just 0.5% of all Australian observations on iNaturalist. Species diversity follows a similar pattern, with animals constituting 58.9% of recorded

Australian species, plants 35.6%, fungi 4.7%, and the remaining kingdoms 0.8%.

Animalia

Australian animal observations are dominated by arthropods (51.9%) and chordates (41.8%), with all other phyla being represented by just 6.3% of observations. Most arthropod observations are insects (86.3%), and, indeed, insects comprise 30.5% of all Australian observations and 33.6% of Australian species across all taxa on iNaturalist. The most observed insect group is Lepidoptera (50.4% of all insect observations; Fig. 3).

Birds are strongly over-represented relative to their diversity, comprising 17.3% of Australian observations across all taxa despite comprising only 2.1% of all species. This strong sampling bias towards birds is pervasive across almost all biodiversity data and platforms (Troudet *et al.* 2017), because birds tend to be more charismatic, easier to photograph and easier to identify compared to other taxa (especially invertebrate groups). Within the chordates, fishes are strongly under-sampled relative to their diversity, comprising 50.1% of all identified Australian chordate species on iNaturalist, but only 16.7% of observations.

Plantae

Australian plant observations are almost entirely of vascular plants (96.6%), with bryophytes (1.1%) the next-most observed group. Most vascular plant observations are dicots (Magnoliopsida; 70.1%), followed by monocots (Liliopsida; 23.5%) and ferns (Polypodiopsida; 3.6%). The most observed dicot order is Asterales (asters, bellflowers, fanflowers, and allies; 14.3%), and the most observed monocot order is Asparagales (agaves, orchids, irises and allies; 64.6%).

The most speciose plant order observed in Australia on iNaturalist is Myrtales (myrtales, evening primroses and allies) with 1316 species, closely followed by Fabales (legumes, milkworts and allies) with 1244 species, and Asparagales with 1215 species.

Fungi

Australian fungi observations on iNaturalist are dominated by basidiomycetes both in observations (74.2%) and species (69.5%), with ascomycetes comprising 15.2% of observations and 29.9% of species. At the class level, 95.2% of basidiomycete observations (75 747) and 90% of species (1148) are agaricomycetes.

Applications of iNaturalist data for conservation

With Earth in the midst of 'biological annihilation' as part of the sixth mass extinction (Ceballos *et al.* 2017), it is more important than ever to understand patterns of biodiversity across space and time. This is especially true for Australia, which has more than 1800 threatened species and one of the worst extinction rates globally (Ward *et al.* 2019). However, monitoring threatened species can be difficult as many species' distributions greatly overlap with private land (Bean and Wilcove 1997; Lepczyk 2005) and large-scale ecological monitoring programs are often expensive (Dickinson *et al.* 2012). The value of Australian iNaturalist data for conservation research has recently been realised (Rowley *et al.* 2019; Kirchhoff *et al.* 2021; Turak *et al.* 2020), highlighting the potential of iNaturalist as a powerful tool for the public to collect large quantities of data from private land at little to no cost. An important direction for future research is the quantification of contributions by iNaturalist to understanding biodiversity on private lands, especially through understanding the percentage of observations made on private land in comparison to professional science and other citizen science initiatives.

Threatened species

iNaturalist has potential for understanding the spatial and temporal distribution of threatened species, with more than 29 460 observations of 1101 Australian species with a conservation status of near threatened or higher (Fig. 4). One of the greatest challenges for conservation is detection; many threatened species are cryptic, have low numbers or have very restricted ranges (Campos-Cerqueira and Aide 2016), so estimates of population size are often difficult. By spreading monitoring efforts across a large number of participants, many of whom have access to private land that would otherwise be difficult to monitor, platforms such as iNaturalist allow the expansion of conservation efforts to scales that would otherwise be impossible without citizen scientists (Ellwood *et al.* 2017; Steven *et al.* 2019). Simultaneously, Australian cities are actually threatened species hotspots, with 30% of threatened species found in urban areas (Ives *et al.* 2016; Lloyd *et al.* 2020). Given that Australian observations on iNaturalist show a strong spatial bias towards major cities and urban areas (Fig. 5), iNaturalist is well poised to contribute strongly to threatened species monitoring and conservation more broadly.

The potential value of iNaturalist for conservation-based monitoring is already apparent, with 18 627 iNaturalist records of species with a conservation status of near threatened or above having been exported to the ALA. This value is especially clear for many individual taxa; 27% of all *Caladenia fulva* (endangered) records, almost 31% of all ngwayir (*Pseudocheirus occidentalis*; critically endangered) records, and 66% of all White's seahorse (*Hippocampus whitei*; endangered) records on the ALA are Australian iNaturalist observations. Future research should aim to further quantify the contributions of iNaturalist data to conservation (e.g. Lloyd *et al.* 2020), and understand how these contributions may differ among taxa.

The value of iNaturalist for Australian insects

Despite insect populations across many of the major orders facing threats from a myriad of factors, including climate change, habitat destruction and the systemic use of agricultural pesticides (Harvey *et al.* 2020; Wagner 2020), insects are strongly under-represented in conservation efforts (Didham *et al.* 2020*a*), and, indeed, very few species have been evaluated and assigned a conservation status (Didham *et al.* 2020*b*). Although much of the data documenting insect declines are spatially biased towards North America and Europe (Simmons *et al.* 2019), population declines and the factors driving them have also been identified in an Australian context (Sands 2018). Concurrently, despite progress in recognising the importance of and implementing conservation efforts for Australian insects, there still remain major impediments to the field. Although

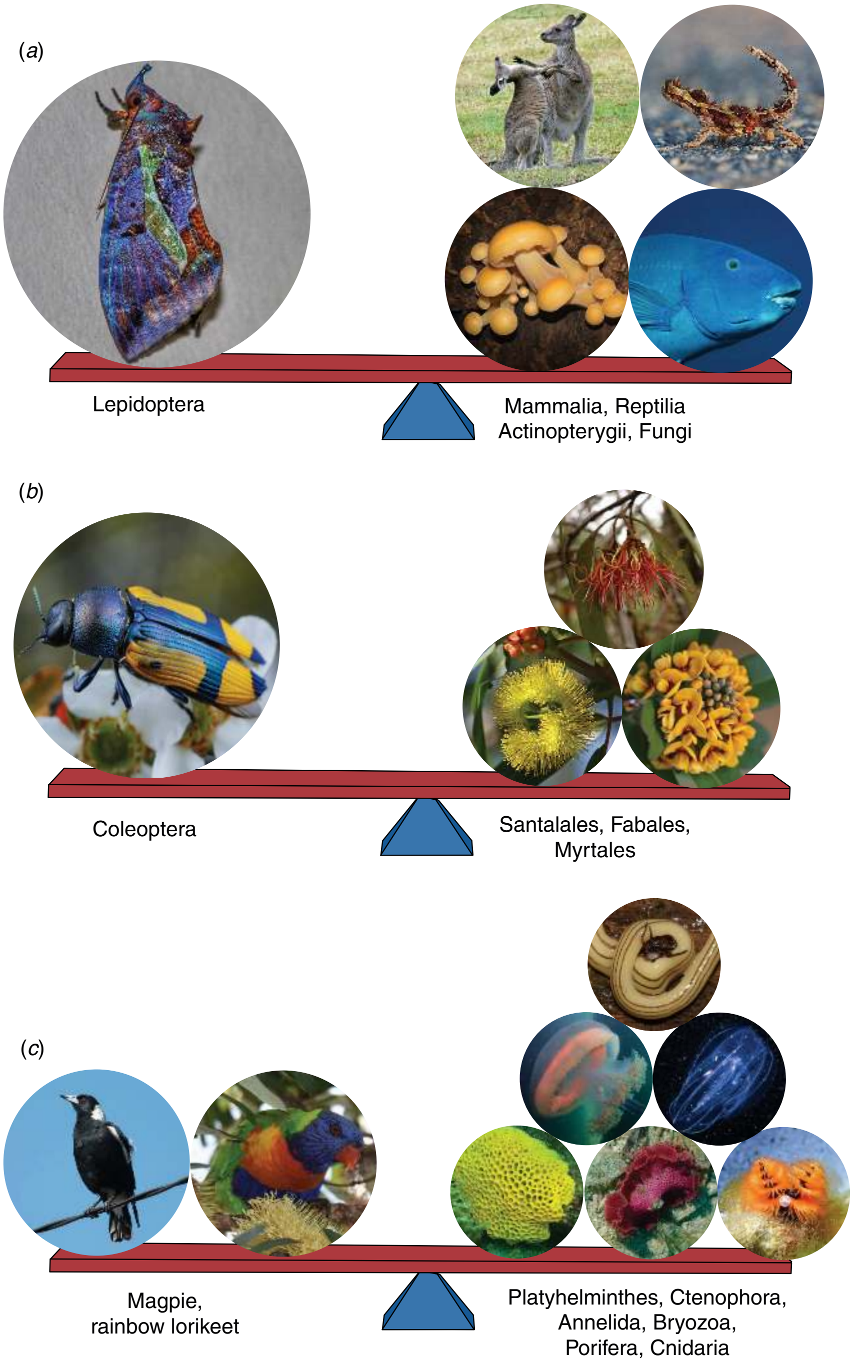

Fig. 3. Visualisation of iNaturalist sampling biases in Australia towards insects and birds. Each seesaw is balanced so that the total observations for the taxa on each side of the seesaw are approximately equal, e.g. in (*c*), the total number of observations for the two most commonly observed Australian bird species on iNaturalist is equal to the total observations for six invertebrate phyla combined. (*a*) Left: David White (@davidgwhite). Right (from top left, clockwise): Deb Raph (@deborod), John Sullivan (@sullivanribbit), Tony Strazzari (@tonydiver), Torbjorn von Strokirch (@blackangus); (*b*) Left: Nick Monaghan (@nickm69). Right (from top, clockwise): Wayne Martin (@w_martin), Loxley Fedec (@npk), Klaus Bohn (@kboh); (*c*) Left: Jack Morgan (@ratite), Dianne Clarke (@dianneclarke). Right (from top, clockwise): Reiner Richter (@reiner), John Turnbull (@johnturnbull), Peter Barfod (@fiftygrit), Trek Hopton (@trekh), David Muirhead (@davemmdave), Sascha Schulz (@sascha_schulz).

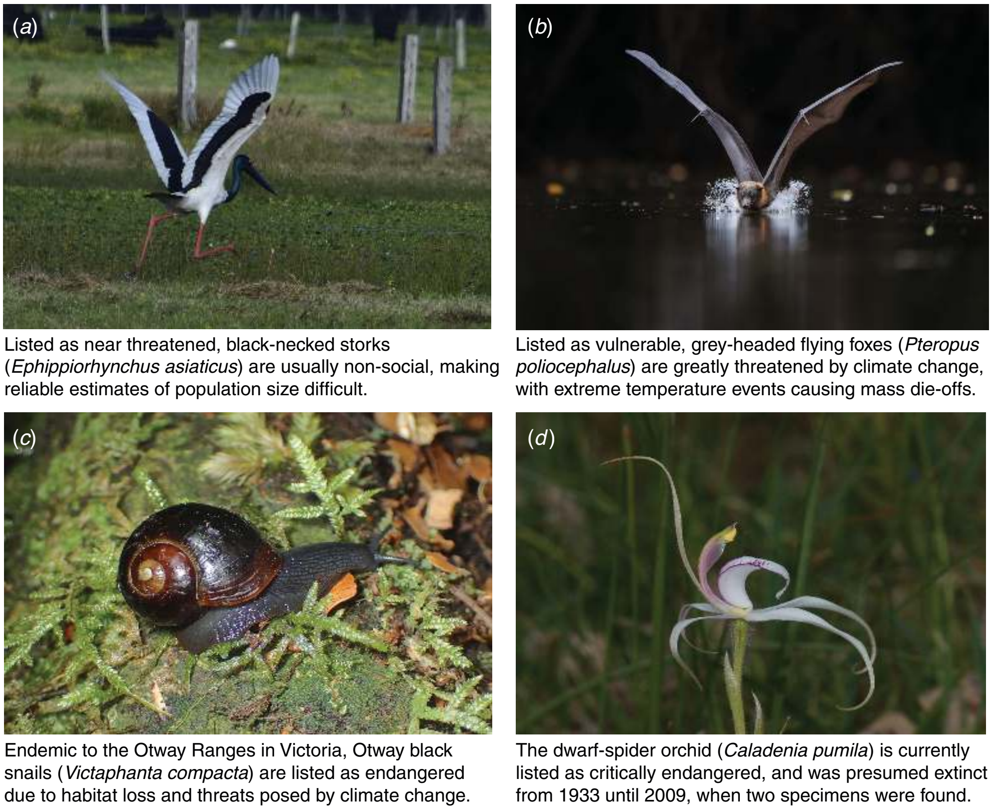

Fig. 4. Examples of Australian observations of threatened species. (*a*) Anthony Katon (@anthonykat); (*b*) Ákos Lumnitzer (@akoslumnitzer); (*c*) John Eichler (@johneichler); (*d*) Reiner Richter (@reiner).

limited funding, decreasing taxonomic expertise, and a lack of public interest all play a role (Taylor *et al.* 2018), the most significant hurdles are the Linnean and Wallacean shortfalls (Brito 2010; Cardoso *et al.* 2011), i.e. that Australian insects constitute a vast assemblage of undescribed species for which little to no data exist, and the geographical distributions of described species are similarly poorly characterised (Sands 2018; Hutchings 2019). Given recording when and where insect species occur is a priority action to combat this data paucity, citizen science is strongly positioned to help address these challenges (New 2018; Didham *et al.* 2020*b*; Wilson *et al.* 2020), and with insects comprising 30.5% of all Australian observations (the highest percentage for the top 15 contributing nations to iNaturalist) across more than 12 000 species, iNaturalist is driving efforts to overcome these shortfalls. Especially notable is the Australian contribution to the *First Known Photographs of Living Specimens* project (https://www.inaturalist.org/projects/first-known-photographs-of-living-specimens), with observations of 183 Australian insect species for which no other photographs of living specimens are readily available online; among these are also the first ever records of several species since their original description (Skejo *et al.* 2020).

Invasive species

As one of the top five drivers of global biodiversity loss, invasive species have been associated with more extinctions in the past 500 years than has any other factor (Blackburn *et al.* 2019), and established populations of invasive species are present within 10 km of the boundaries of almost 90% of the world's protected areas (Liu *et al.* 2020). In Australia, invasive species have enormous ecological and economic impacts, incurring a cost of more than AU$13.6 billion (losses and control) in the 2011–2012 financial year alone (Hoffmann and Broadhurst 2016). Australian citizen science platforms such as FeralScan and MyPestGuide™ play an integral role in modelling the distribution of invasive species (Roy-Dufresne *et al.* 2019) and facilitating pest surveillance for biosecurity (Emery *et al.* 2016). With 70 638 observations of 932 introduced species in Australia, many of which are also invasive, iNaturalist is well positioned to contribute strongly to this field, particularly for significant invasive species such as the red fox (*Vulpes vulpes*; 1475 observations), cane toad (*Rhinella marinus*; 1043 observations) and lantana (*Lantana camara*; 791 observations).

Spatial summary of Australian iNaturalist data

Although Australian observations span the continent and much of its islands, there are strong spatial biases towards major cities, especially along the eastern and south-eastern coasts (Fig. 5). These biases are consistent with many citizen science initiatives (Geldmann *et al.* 2016; Callaghan *et al.* 2020*c*), and, indeed, ecological research more broadly (Boakes *et al.* 2010; Piccolo *et al.* 2020). This pattern is especially pronounced for Australian citizen science initiatives that contribute to threatened species monitoring and conservation, with strong correlations between

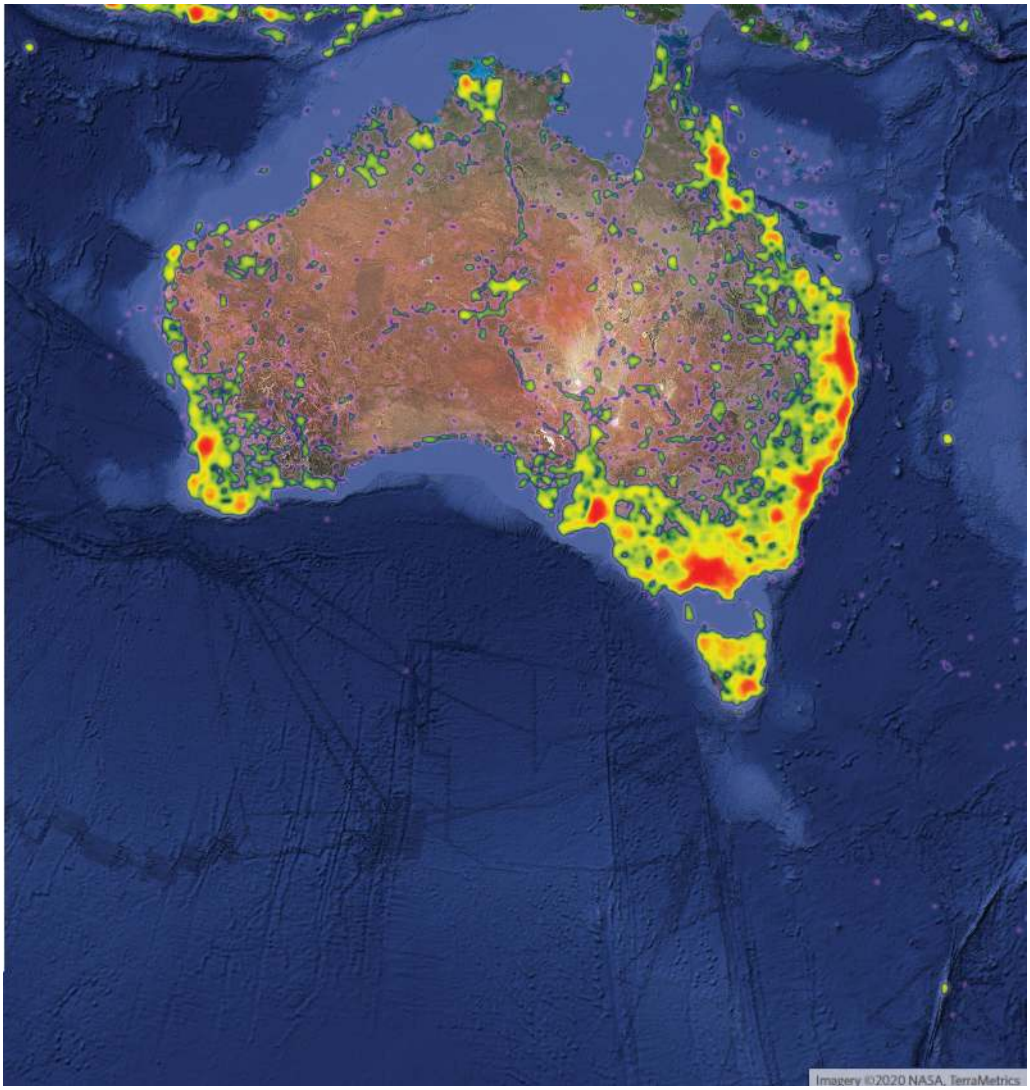

Fig. 5. Heat map for all observations within continental Australia, islands under Australian jurisdiction, and the waters constituting Australia's Exclusive Economic Zone. The warmer the colour, the greater the density of observations. Note that the colours code for relative density, not absolute density. Note the high density of observations around each capital city, as well as power-user driven, regional hotspots such as near eastern Victoria (Reiner Richter, @reiner), Taree (Victor Fazio III, @vicfazio3) and Coffs Harbour (Nick Lambert, @nicklambert). This figure was adapted from the inbuilt heat map available at www.inaturalist.org/observations/map#2/0/0. Note that the default zoom level is #2; we zoomed to level #6, and then manually stitched together 25 individual screenshots of Australia and its waters.

project density and population density along the south-eastern and south-western coasts (Lloyd *et al.* 2020), mirroring the patterns seen in Fig. 5. Although many of the Australian iNaturalist observation hotspots are associated with the most populous capital cities, others are also driven by the presence of research institutions, such as the efforts of James Cook University students at Cairns, and the contributions of individual power users.

But despite strong spatial coverage along the eastern and south-eastern coasts, and south-western corner, there are still many large areas of Australia with little or no iNaturalist observations. Outside small, largely tourist-driven clusters around Alice Springs and Uluru–Kata Tjuta National Park, much of Australia's arid interior is extremely data deficient, including vast tracts of the Nullabor, Great Victoria Desert and Simpson Desert. This under-sampling is also reflected in professional science for many taxa, especially at local scales (Schmidt-Lebuhn *et al.* 2012), highlighting a key target area for future sampling.

Another conspicuous spatial gap exists in tropical northern Australia, with most of Arnhem Land being unsampled by iNaturalist. Improving sampling across this region is crucial given its high biodiversity and endemicity (Woinarski *et al.* 2009), the recent drastic decline of its small to medium mammal biota (Einoder *et al.* 2018), and the under-sampling of its fauna even in professional science and for charismatic taxa such as

Table 2. Selected examples of successful Australian iNaturalist projects

Project	Focus(es)	Observations	Species	Observers	Identifiers
Australasian Fishes (https://www.inaturalist.org/projects/australasian-fishes)	Ray-finned fishes (Actinopterygii); lobe-finned fishes (Sarcopterygii); jawless fishes (Agnatha); sharks and rays (Elasmobranchii)	99 527	2664	3129	1670
Backyard Species Discovery with Bush Blitz (Australia) (https://www.inaturalist.org/projects/backyard-species-discovery-with-bush-blitz-australia)	All taxa	109 122	8455	179	2362
Fungimap Australia (https://www.inaturalist.org/projects/fungimap-australia)	Fungi	30 216	1032	343	602
Cicadas of Australia (https://www.inaturalist.org/projects/cicadas-of-australia)	Cicadas (Cicadoidea)	10 402	166	1266	374
Environment Recovery Project: Australian Bushfires (https://www.inaturalist.org/projects/environment-recovery-project-australian-bushfires)	Observations from areas affected by the 2019–2020 bushfire season, and subsequent bushfires	9980	1846	308	624

mammals (Ziembicki *et al.* 2015). Similarly, despite the region's high threatened species richness, citizen science initiatives targeting these species are relatively low in number (Lloyd *et al.* 2020), reinforcing the value of engaging citizen scientists across this region.

Perhaps the most poorly sampled regions of Australia on iNaturalist are its offshore waters, particularly those beyond the continental shelf (>200 m water depth). These zones are characterised by low numbers of specimens, gaps in taxonomic knowledge and many species awaiting discovery and description (Williams *et al.* 2018). Although this data paucity is understandable given the inaccessibility of these regions and habitats, especially to citizen scientists, it highlights the importance of diversifying and recruiting new iNaturalist users from sectors such as commercial fisheries.

Leveraging an existing platform for focussed projects

One of iNaturalist's most powerful attributes is the 'Project' feature. Projects allow users to filter and collect observations either automatically on the basis of their metadata, such as spatial coordinates or dates of observation (collection projects); or, manually by collating observations with some unifying theme, such as observations of feathers or records of predator–prey relationships (traditional projects). Although iNaturalist is broadly an unstructured, opportunistic data collection platform, projects provide the scope for more structured protocols and sampling designs; many projects are designed around customisable observation fields or the collection of additional metadata unique to a specific scientific objective or hypothesis (e.g. host plant, substrate, or habitat information), highlighting iNaturalist's potential to shift towards semi-structured data collection when used in this way. Given projects are simple and fast to create, intuitive to interact with, and require minimal manipulation to be effective, they are an ideal tool for collecting both spatiotemporal and secondary data. Perhaps the greatest strength of projects is that they offer existing digital infrastructure ready-made for immediate data collection, obviating the need for project managers to build any data collection tools themselves.

Factors driving successful projects

Many of the most successful Australian projects (Table 2) are driven by one, or both, of two key factors. First, although many projects have a specific taxonomic or ecological focus, successful projects often collect observations and data at large spatial scales, maximising participation and allowing the development of a diverse community of users. Second, successful projects are often monitored and/or administrated by a core group of professional experts who consistently provide identifications and teach other users, driving the creation of a strong community with similar interests. This opportunity to collaborate with and learn from professionals is an important and highly valued aspect of citizen science initiatives (Johnson *et al.* 2014; Steven *et al.* 2019), and indeed in many cases, this learning is mutual (Dowthwaite and Sprinks 2019; Pearse 2020), further motivating the professionals.

Australasian Fishes, the longest-running and most successful Australian iNaturalist project, highlights the value of these two factors for project success. Created in late 2016 by Mark McGrouther (@markmcg), the former Ichthyology Collection Manager at the Australian Museum, the project focuses on fishes, sharks and rays across Australia and New Zealand. Almost 15% of all users who have contributed data for Australia have also contributed to *Australasian Fishes*, with an extensive network of museum curators, taxonomic experts, researchers and many passionate amateur naturalists from all around Australia helping build a strong community. These successes are reflected in the use of photographs and observation metadata from the project in research (e.g. Booth and Sear 2018; Fetterplace *et al.* 2018). *Australasian Fishes* members were also heavily involved in the first ever record of a hoodwinker sunfish (*Mola tecta*) in the northern hemisphere, which made international headlines in 2019 (https://www.bbc.com/news/world-us-canada-47424072). *Cicadas of Australia* is another popular taxon-specific, community-driven project, with almost 1300 contributors across Australia able to learn from a core group of Australian cicada experts, and, in return, provide valuable local knowledge that also benefits the experts.

Benefits of successful projects

Designed to rapidly collect data after the devastating 2019–2020 Australian bushfire season, the *Environment Recovery Project* run by the University of New South Wales' Centre for Ecosystem Science has been hugely productive. The easy to use, ready-made digital infrastructure provided by the project feature, combined with a strong media campaign (e.g. https://www.abc.net.au/triplej/programs/hack/citizen-science-project-bushfire-recovery-needs-your-help/11910486), helped drive the upload of 10 000 observations by more than 300 observers across south-eastern Australia in just 10 months, including data collected within days of fires occurring. These successes have seen the project already generate research output (Kirchhoff *et al.* 2021), with invaluable data tracking the recovery of Australian ecosystems continuing to be collected.

Overcoming sampling biases towards charismatic taxa is another benefit of successful projects. Fungal taxonomy and conservation are largely neglected fields, especially in Australia; a paucity of mycologists, the cryptic nature of many species (especially owing to the ephemerality of fruiting bodies for many groups), and the prominence of pathogenic species in the public consciousness (Irga *et al.* 2018) have all contributed to a lack of knowledge of this group. Given that the conservation of fungi requires an understanding of how many species exist and the resolution of taxonomic opacity, iNaturalist Australia is well placed to contribute significantly, with *Fungimap Australia* featuring more than 30 000 observations of over 1000 species. The promotion of this project and the recruitment of professional mycologists to teach and collaborate with citizen scientists (Grube *et al.* 2017) will improve the quality of the fungal dataset of iNaturalist Australia and help drive conservation efforts.

The robust existing data collection frameworks created by projects also help attract more professional scientists. As Australia's largest biodiversity discovery program, Bush Blitz's involvement with iNaturalist through the *Backyard Species Discovery with Bush Blitz* project has driven a large uptick in Australian taxonomic experts joining iNaturalist, especially for many less charismatic taxa. This recruitment has been crucial for driving greater engagement between experts and amateur naturalists. An important future area will be quantifying the impact of these experts with respect to data quality and accuracy of identifications, similar to previous analyses of identification accuracy by platforms such as iSpot (Silvertown *et al.* 2015).

Directions for the future of iNaturalist in Australia

With Australian contributions to iNaturalist continuing to accelerate exponentially across all metrics, including number of observations, observers, and species, increasingly large datasets will become available to researchers in the future. By optimising when, where and how biodiversity is sampled and identified (Callaghan *et al.* 2019), the scope for research opportunities and applications of the data is immense. We propose the following four key future research directions for the use of iNaturalist data by Australian ecological researchers: (1) use of existing data to model species distributions in space and time, (2) extraction of secondary data from observations, (3) increased collaboration with taxonomic experts, and (4) dynamic use of the data and integration into policy planning.

Given the scale of massive citizen science datasets, many applications of these data lie in estimating the abundance of species across space and time (Tulloch *et al.* 2013; Chandler *et al.* 2017; Callaghan *et al.* 2020*b*). Indeed, outside Australia, iNaturalist data have already been used to inform local population trends (Erickson and Burt 2019) and model species distributions at a continental scale (Wang *et al.* 2018). With over 1.6 million observations having already been submitted for Australia, a major focus of research in the near future should be its use for modelling species distributions and detecting population trends in space and time. The paucity of current research from an Australian iNaturalist perspective highlights the need to focus on large-scale trends using massive datasets; many of the papers that do utilise Australian iNaturalist data are brief records of range shifts or rare species at novel locations (Booth and Sear 2018; Hewish 2019; Schubert 2020), whereas other papers have used Australian data as part of assessments of data quality (Hochmair *et al.* 2020). Although iNaturalist is largely restricted to presence-only data, there is an increasing number of methods able to account for missing absence data (Fithian *et al.* 2015; Roberts *et al.* 2017), mostly by integrating citizen science data with data from other sources such as remote sensing or professional surveys (He *et al.* 2015; Pacifici *et al.* 2017).

iNaturalist is also an untapped resource for valuable secondary data beyond spatiotemporal coordinates on a map (Gazdic and Groom 2019; Callaghan *et al.* 2020*b*). Although this potential has been recently realised in North America, with studies undertaking continent-scale assessments of phenotypic (Drury *et al.* 2019) and phenological data (Barve *et al.* 2020) using iNaturalist observations, these applications are mostly unrealised in an Australian context. Capitalising on this secondary information, for example, extracting plant–pollinator relationships or colour morphs across a species' range, will vastly expand the already considerable potential of Australian iNaturalist observations as a source for understanding biodiversity (Tulloch *et al.* 2013).

A crucial direction to help facilitate improvement of the data is the continued recruitment of Australian taxonomic experts, particularly for esoteric taxa for which iNaturalist currently has few trained identifiers. Greater involvement by these experts will facilitate learning by citizen scientists (Domroese and Johnson 2017; Parrish *et al.* 2018), motivating them to make more and better observations (e.g. learning which features are required for different taxa, and photographing these accordingly to promote easier identification). In turn, this will improve the data further, thus attracting more experts in a positive feedback loop (Fig. 6).

Finally, we highlight the need for, and importance of, using Australian iNaturalist data to inform policy. Scientific policy decisions are often dictated, for the worse, by the costs associated with data collection and research (Vuong 2018), and these decisions can have significant negative repercussions for

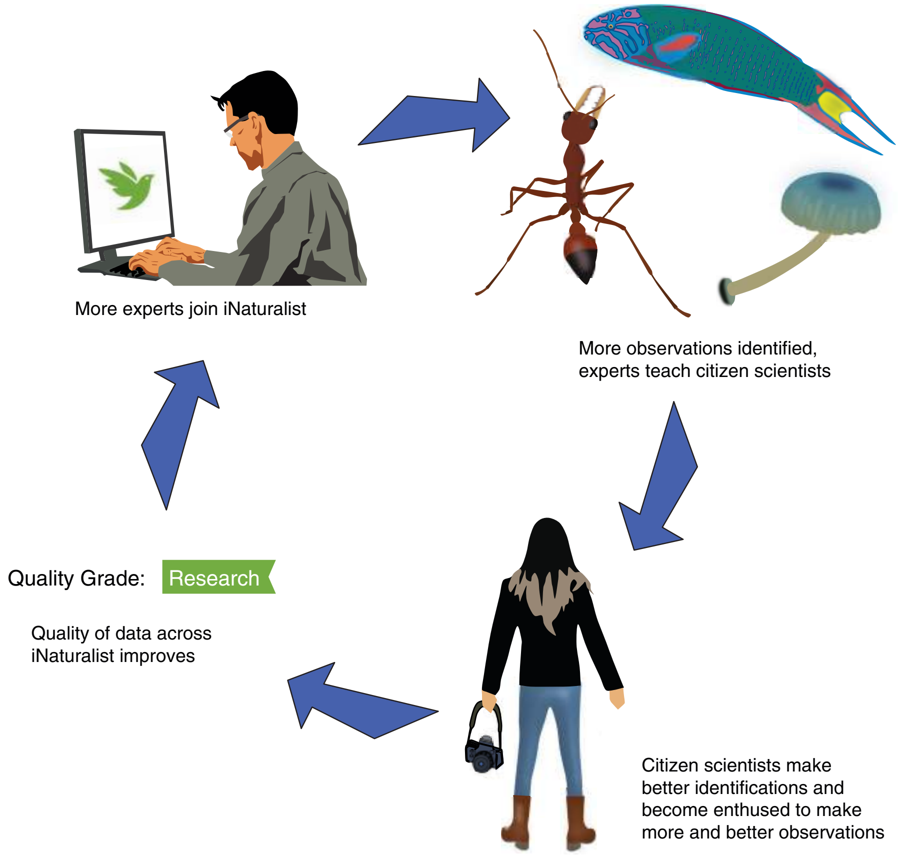

Fig. 6. Conceptual figure showing the positive feedback loop as iNaturalist continues to grow in Australia. As more taxonomic experts join iNaturalist, more observations will increase the bioliteracy of the data, providing more data for ecological and conservation research questions in Australia.

biodiversity (Azevedo-Santos *et al.* 2017). Because citizen science data are typically collected and verified at little or no cost, a model followed by iNaturalist, integration with professional data collection greatly reduces the costs of ecological monitoring and expedites scientific discoveries (Cavalier and Kennedy 2016; Nascimento *et al.* 2018), providing incentivisation for policymakers to utilise these data so as to implement meaningful policies. This is especially important in Australian cities, where the disproportionate presence of threatened species compared with less urban areas provides many opportunities for conservation practitioners and policymakers to engage with citizen science (Ives *et al.* 2016). Collaboration within iNaturalist is also a boon for policy; the ability for taxonomic experts to review data points and provide identifications in real time increases the legitimacy of the data and better informs policy and legislation (Couvet *et al.* 2008; Jones *et al.* 2019), with the expediency of this data filtering being especially important to ameliorate the consistently slow transfer of research findings into policy (Dunn *et al.* 2018). Given that the science–policy interface in Australian government has been historically characterised by conflicting ideologies, poor communication and systemic inflexibility (Hickey *et al.* 2013), iNaturalist Australia has a critical role to play.

Conclusions

Australia's contributions to iNaturalist are significant (e.g. Fig. 2). Moving beyond singular records of interesting and unique data points (e.g. Fig. 1) and, instead, focusing on the integration of Australian iNaturalist data into professional ecological research is an important future step towards fully realising the value of these data. That citizen science data can significantly contribute to broad-scale ecological databases and drive research in spatial ecology, conservation, and macroecology is clear (Kobori *et al.* 2016; Poisson *et al.* 2020), and although well structured citizen science projects produce the most robust data, even projects with opportunistic data collection and little participant training can still contribute to ecological monitoring (Brown and Williams 2019). Given that the establishment of robust databases is a crucial facet of ecological research (Osawa 2019), iNaturalist is well positioned to be a major source of ecological data into the future to better understand Australian ecology and conservation. Although the value of these data for use in broad ecological research and biodiversity monitoring is increasingly being recognised, there is still great potential for improvement. The optimisation of data sampling, recruitment of more taxonomic experts, and increased exploration of secondary data integration are all important drivers of this improvement, and will drive better science–policy communication.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

We thank the thousands of contributors who have uploaded observations of Australian species, and identified these observations for others. Thanks also to Mark McGrouther for providing material for the Australasian Fishes section. Two anonymous reviewers provided thoughtful comments that substantially improved this manuscript. This research did not receive any specific funding.

References

Aceves-Bueno, E., Adeleye, A. S., Feraud, M., Huang, Y., Tao, M., Yang, Y., and Anderson, S. E. (2017). The accuracy of citizen science data: a quantitative review. *Bulletin of the Ecological Society of America* **98**, 278–290. doi:10.1002/bes2.1336

Agarwal, M. (2017). First record of *Dendronotus orientalis* (Baba, 1932) (Nudibranchia: Dendronotidae) in the temperate eastern Pacific. *BioInvasions Records* **6**, 135–138. doi:10.3391/bir.2017.6.2.08

Azevedo-Santos, V. M., Fearnside, P. M., Oliveira, C. S., Padial, A. A., Pelicice, F. M., Lima, D. P., Simberloff, D., Lovejoy, T. E., Magalhaes, A. L., Orsi, M. L., and Agostinho, A. A. (2017). Removing the abyss between conservation science and policy decisions in Brazil. *Biodiversity and Conservation* **26**, 1745–1752. doi:10.1007/s10531-017-1316-x

Barve, V. V., Brenskelle, L., Li, D., Stucky, B. J., Barve, N. V., Hantak, M. M., McLean, B. S., Paluh, D. J., Oswald, J. A., Belitz, M. W., and Folk, R. A. (2020). Methods for broad-scale plant phenology assessments using citizen scientists' photographs. *Applications in Plant Sciences* **8**, e11315. doi:10.1002/aps3.11315

Baumann, J. M., Walker, K., Threlfall, C., and Williams, N. S. (2016). African Carder bee, *Afranthidium (Immanthidium) repetitum* (Hymenoptera: Megachilidae): a new exotic species for Victoria. *Victorian Naturalist* **133**, 21.

Bean, M. J., and Wilcove, D. S. (1997). The private-land problem. *Conservation Biology* **11**, 1–2. doi:10.1046/j.1523-1739.1997.011001001.x

Bird, T. J., Bates, A. E., Lefcheck, J. S., Hill, N. A., Thomson, R. J., Edgar, G. J., Stuart-Smith, R. D., Wotherspoon, S., Krkosek, M., Stuart-Smith, J. F., Pecl, G. T., Barrett, N., and Frusher, S. (2014). Statistical solutions for error and bias in global citizen science datasets. *Biological Conservation* **173**, 144–154. doi:10.1016/j.biocon.2013.07.037

Blackburn, T. M., Bellard, C., and Ricciardi, A. (2019). Alien versus native species as drivers of recent extinctions. *Frontiers in Ecology and the Environment* **17**, 203–207. doi:10.1002/fee.2020

Boakes, E. H., McGowan, P. J., Fuller, R. A., Chang-qing, D., Clark, N. E., O'Connor, K., and Mace, G. M. (2010). Distorted views of biodiversity: spatial and temporal bias in species occurrence data. *PLoS Biology* **8**, e1000385. doi:10.1371/journal.pbio.1000385

Booth, D. J., and Sear, J. (2018). Coral expansion in Sydney and associated coral-reef fishes. *Coral Reefs* **37**, 995. doi:10.1007/s00338-018-1727-5

Brito, D. (2010). Overcoming the Linnean shortfall: data deficiency and biological survey priorities. *Basic and Applied Ecology* **11**, 709–713. doi:10.1016/j.baae.2010.09.007

Brown, E. D., and Williams, B. K. (2019). The potential for citizen science to produce reliable and useful information in ecology. *Conservation Biology* **33**, 561–569. doi:10.1111/cobi.13223

Burgess, H. K., DeBey, L. B., Froehlich, H. E., Schmidt, N., Theobald, E. J., Ettinger, A. K., HilleRisLambers, J., Tewksbury, J., and Parrish, J. K. (2017). The science of citizen science: exploring barriers to use as a primary research tool. *Biological Conservation* **208**, 113–120. doi:10.1016/j.biocon.2016.05.014

Callaghan, C. T., Poore, A. G., Major, R. E., Rowley, J. J., and Cornwell, W. K. (2019). Optimizing future biodiversity sampling by citizen scientists. *Proceedings. Biological Sciences* **286**, 20191487. doi:10.1098/rspb.2019.1487

Callaghan, C. T., Ozeroff, I., Hitchcock, C., and Chandler, M. (2020*a*). Capitalizing on opportunistic science data to monitor urban biodiversity: a multi-taxa framework. *Biological Conservation* **251**, 108753.

Callaghan, C. T., Poore, A. G., Mesaglio, T., Moles, A. T., Nakagawa, S., Roberts, C., Rowley, J. J., Vergés, A., Wilshire, J. H., and Cornwell, W. K. (2020*b*). Three frontiers for the future of biodiversity research using citizen science data. *BioScience* **71**, 55–63. doi:10.1093/biosci/biaa131

Callaghan, C. T., Roberts, J. D., Poore, A. G., Alford, R. A., Cogger, H., and Rowley, J. J. (2020*c*). Citizen science data accurately predicts expert-derived species richness at a continental scale when sampling thresholds are met. *Biodiversity and Conservation* **29**, 1323–1337. doi:10.1007/s10531-020-01937-3

Campos-Cerqueira, M., and Aide, T. M. (2016). Improving distribution data of threatened species by combining acoustic monitoring and occupancy modelling. *Methods in Ecology and Evolution* **7**, 1340–1348. doi:10.1111/2041-210X.12599

Cardoso, P., Erwin, T. L., Borges, P. A., and New, T. R. (2011). The seven impediments in invertebrate conservation and how to overcome them. *Biological Conservation* **144**, 2647–2655. doi:10.1016/j.biocon.2011.07.024

Cavalier, D., and Kennedy, E. B. (Eds) (2016). 'The Rightful Place of Science: Citizen Science.' (Consortium for Science, Policy & Outcomes.)

Ceballos, G., Ehrlich, P. R., and 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

Chandler, M., See, L., Copas, K., Bonde, A. M., López, B. C., Danielsen, F., Legind, J. K., Masinde, S., Miller-Rushing, A. J., Newman, G., and Rosemartin, A. (2017). Contribution of citizen science towards international biodiversity monitoring. *Biological Conservation* **213**, 280–294. doi:10.1016/j.biocon.2016.09.004

Couvet, D., Jiguet, F., Julliard, R., Levrel, H., and Teyssedre, A. (2008). Enhancing citizen contributions to biodiversity science and public policy. *Interdisciplinary Science Reviews* **33**, 95–103. doi:10.1179/030801808X260031

Danielsen, F., Burgess, N. D., and Balmford, A. (2005). Monitoring matters: examining the potential of locally-based approaches. *Biodiversity and Conservation* **14**, 2507–2542. doi:10.1007/s10531-005-8375-0

de Vries, M., Land-Zandstra, A., and Smeets, I. (2019). Citizen scientists' preferences for communication of scientific output: a literature review. *Citizen Science: Theory and Practice* **4**, 1–13.

Dickinson, J. L., Shirk, J., Bonter, D., Bonney, R., Crain, R. L., Martin, J., Phillips, T., and Purcell, K. (2012). The current state of citizen science as a tool for ecological research and public engagement. *Frontiers in Ecology and the Environment* **10**, 291–297. doi:10.1890/110236

Didham, R. K., Barbero, F., Collins, C. M., Forister, M. L., Hassall, C., Leather, S. R., Packer, L., Saunders, M. E., and Stewart, A. J. (2020*a*). Spotlight on insects: trends, threats and conservation challenges. *Insect Conservation and Diversity* **13**, 99–102. doi:10.1111/icad.12409

Didham, R. K., Basset, Y., Collins, C. M., Leather, S. R., Littlewood, N. A., Menz, M. H., Müller, J., Packer, L., Saunders, M. E., Schönrogge, K., and Stewart, A. J. (2020*b*). Interpreting insect declines: seven challenges and a way forward. *Insect Conservation and Diversity* **13**, 103–114. doi:10.1111/icad.12408

Domroese, M. C., and Johnson, E. A. (2017). Why watch bees? Motivations of citizen science volunteers in the Great Pollinator Project. *Biological Conservation* **208**, 40–47. doi:10.1016/j.biocon.2016.08.020

Dowthwaite, L., and Sprinks, J. (2019). Citizen science and the professional–amateur divide: lessons from differing online practices. *Journal of Science Communication* **18**, A06. doi:10.22323/2.18010206

Drury, J. P., Barnes, M., Finneran, A. E., Harris, M., and Grether, G. F. (2019). Continent-scale phenotype mapping using citizen scientists' photographs. *Ecography* **42**, 1436–1445. doi:10.1111/ecog.04469

Dunn, G., Bos, J. J., and Brown, R. R. (2018). Mediating the science-policy interface: insights from the urban water sector in Melbourne, Australia. *Environmental Science & Policy* **82**, 143–150. doi:10.1016/j.envsci.2018.02.001

Einoder, L. D., Southwell, D. M., Lahoz-Monfort, J. J., Gillespie, G. R., Fisher, A., and Wintle, B. A. (2018). Occupancy and detectability modelling of vertebrates in northern Australia using multiple sampling methods. *PLoS One* **13**, e0203304. doi:10.1371/journal.pone.0203304

Ellwood, E. R., Crimmins, T. M., and Miller-Rushing, A. J. (2017). Citizen science and conservation: recommendations for a rapidly moving field. *Biological Conservation* **208**, 1–4. doi:10.1016/j.biocon.2016.10.014

Emery, R. N., Fagan, L., McCauley, R., Hardie, D., Hammond, N., Cook, D., Wright, D., Cousins, D., Russell, J., and Garel, N. (2016). MyPestGuide – the 'BEST' suite of biosecurity engagement and surveillance tools. In '2016 International Congress of Entomology'. (Entomological Society of America: Annapolis, MD, USA.)

Erickson, R. A., and Burt, W. G. (2019). Additional information on a nonnative whiptail population (*Aspidoscelis flagellicauda/sonorae* complex) in suburban Orange County, California. *Bulletin of the Southern California Academy of Sciences* **118**, 76–78. doi:10.3160/0038-3872-118.1.76

Fetterplace, L. C., Turnbull, J. W., Knott, N. A., and Hardy, N. A. (2018). The devil in the deep: expanding the known habitat of a rare and protected fish. *European Journal of Ecology* **4**, 22–29. doi:10.2478/eje-2018-0003

Fithian, W., Elith, J., Hastie, T., and Keith, D. A. (2015). Bias correction in species distribution models: pooling survey and collection data for multiple species. *Methods in Ecology and Evolution* **6**, 424–438. doi:10.1111/2041-210X.12242

Gazdic, M., and Groom, Q. (2019). iNaturalist is an unexploited source of plant–insect interaction data. *Biodiversity Information Science and Standards* **3**, e37303. doi:10.3897/biss.3.37303

Geldmann, J., Heilmann-Clausen, J., Holm, T. E., Levinsky, I., Markussen, B., Olsen, K., Rahbek, C., and Tøttrup, A. P. (2016). What determines spatial bias in citizen science? Exploring four recording schemes with different proficiency requirements. *Diversity & Distributions* **22**, 1139–1149. doi:10.1111/ddi.12477

Grube, M., Gaya, E., Kauserud, H., Smith, A. M., Avery, S. V., Fernstad, S. J., Muggia, L., Martin, M. D., Eivindsen, T., Koljalg, U., and Bendiksby, M. (2017). The next generation fungal diversity researcher. *Fungal Biology Reviews* **31**, 124–130. doi:10.1016/j.fbr.2017.02.001

Harvey, J. A., Heinen, R., Armbrecht, I., Basset, Y., Baxter-Gilbert, J. H., Bezemer, T. M., Böhm, M., Bommarco, R., Borges, P. A., Cardoso, P., and Clausnitzer, V. (2020). International scientists formulate a roadmap for insect conservation and recovery. *Nature Ecology & Evolution* **4**, 174–176. doi:10.1038/s41559-019-1079-8

He, K. S., Bradley, B. A., Cord, A. F., Rocchini, D., Tuanmu, M. N., Schmidtlein, S., Turner, W., Wegmann, M., and Pettorelli, N. (2015). Will remote sensing shape the next generation of species distribution models? *Remote Sensing in Ecology and Conservation* **1**, 4–18. doi:10.1002/rse2.7

Hewish, M. (2019). Swamp Bluet *Coenagrion lyelli* Tillyard (Odonata: Zygoptera: Coenagrionidae) In South Australia. *Victorian Entomologist* **49**, 81.

Hickey, G. M., Forest, P., Sandall, J. L., Lalor, B. M., and Keenan, R. J. (2013). Managing the environmental science–policy nexus in government: perspectives from public servants in Canada and Australia. *Science & Public Policy* **40**, 529–543. doi:10.1093/scipol/sct004

Hochmair, H. H., Scheffrahn, R. H., Basille, M., and Boone, M. (2020). Evaluating the data quality of iNaturalist termite records. *PLoS One* **15**, e0226534. doi:10.1371/journal.pone.0226534

Hoffmann, B. D., and Broadhurst, L. M. (2016). The economic cost of managing invasive species in Australia. *NeoBiota* **31**, 1–18. doi:10.3897/neobiota.31.6960

Hutchings, P. (2019). An advocate for taxonomic research in Australia. *Pacific Conservation Biology* **25**, 34–36. doi:10.1071/PC17033

Irga, P. J., Barker, K., and Torpy, F. R. (2018). Conservation mycology in Australia and the potential role of citizen science. *Conservation Biology* **32**, 1031–1037. doi:10.1111/cobi.13121

Isaac, N. J., van Strien, A. J., August, T. A., de Zeeuw, M. P., and Roy, D. B. (2014). Statistics for citizen science: extracting signals of change from noisy ecological data. *Methods in Ecology and Evolution* **5**, 1052–1060. doi:10.1111/2041-210X.12254

Ives, C. D., Lentini, P. E., Threlfall, C. G., Ikin, K., Shanahan, D. F., Garrard, G. E., Bekessy, S. A., Fuller, R. A., Mumaw, L., Rayner, L., and Rowe, R. (2016). Cities are hotspots for threatened species. *Global Ecology and Biogeography* **25**, 117–126. doi:10.1111/geb.12404

Jain, A., Chan, S. K. M., Soh, M., and Chow, L. (2019). Rediscovery of the orange gull butterfly, *Cepora iudith malaya*, in Singapore. *Singapore Biodiversity Records* 22–23.

Johnson, M. F., Hannah, C., Acton, L., Popovici, R., Karanth, K. K., and Weinthal, E. (2014). Network environmentalism: citizen scientists as agents for environmental advocacy. *Global Environmental Change* **29**, 235–245. doi:10.1016/j.gloenvcha.2014.10.006

Jones, C. D., Glon, M. G., Cedar, K., Paiero, S. M., Pratt, P. D., and Preney, T. J. (2019). First record of paintedhand mudbug (*Lacunicambarus polychromatus*) in Ontario and Canada and the significance of iNaturalist in making new discoveries. *Canadian Field Naturalist* **133**, 160–166. doi:10.22621/cfn.v133i2.2223

Kirchhoff, C., Callaghan, C. T., Keith, D. A., Indiarto, D., Taseski, G., Ooi, M. K., Le Breton, T. D., Mesaglio, T., Kingsford, R. T., and Cornwell, W. (2021). Rapidly mapping fire effects on biodiversity at a large-scale using citizen science. *The Science of the Total Environment* **755**, 142348. doi:10.1016/j.scitotenv.2020.142348

Kobori, H., Dickinson, J. L., Washitani, I., Sakurai, R., Amano, T., Komatsu, N., Kitamura, W., Takagawa, S., Koyama, K., Ogawara, T., and Miller-Rushing, A. J. (2016). Citizen science: a new approach to advance ecology, education, and conservation. *Ecological Research* **31**, 1–19. doi:10.1007/s11284-015-1314-y

Lehtinen, R. M., Carlson, B. M., Hamm, A. R., Riley, A. G., Mullin, M. M., and Gray, W. J. (2020). Dispatches from the neighborhood watch: using citizen science and field survey data to document color morph frequency in space and time. *Ecology and Evolution* **10**, 1526–1538. doi:10.1002/ece3.6006

Lepczyk, C. A. (2005). Integrating published data and citizen science to describe bird diversity across a landscape. *Journal of Applied Ecology* **42**, 672–677. doi:10.1111/j.1365-2664.2005.01059.x

Liu, X., Blackburn, T. M., Song, T., Wang, X., Huang, C., and Li, Y. (2020). Animal invaders threaten protected areas worldwide. *Nature Communications* **11**, 1–9.

Lloyd, T. J., Fuller, R. A., Oliver, J. L., Tulloch, A., Barnes, M., and Steven, R. (2020). Estimating the spatial coverage of citizen science for monitoring threatened species. *Global Ecology and Conservation* **23**, e01048. doi:10.1016/j.gecco.2020.e01048

McKinley, D. C., Miller-Rushing, A. J., Ballard, H. L., Bonney, R., Brown, H., Cook-Patton, S. C., Evans, D. M., French, R. A., Parrish, J. K., Phillips, T. B., and Ryan, S. F. (2017). Citizen science can improve conservation science, natural resource management, and environmental protection. *Biological Conservation* **208**, 15–28. doi:10.1016/j.biocon.2016.05.015

Nascimento, S., Rubio Iglesias, J. M., Owen, R., Schade, S., and Shanley, L. (2018). Citizen science for policy formulation and implementation. In

‘Citizen Science: Innovation in Open Science, Society and Policy’. (Eds S. Hecker, M. Haklay, A. Bowser, Z. Makuch, J. Vogel, and A. Bonn.) pp. 219–240. (UCL Press: London, UK.)

New, T. R. (2018). Promoting and developing insect conservation in Australia’s urban environments. *Austral Entomology* **57**, 182–193. doi:10.1111/aen.12332

Osawa, T. (2019). Perspectives on biodiversity informatics for ecology. *Ecological Research* **34**, 446–456. doi:10.1111/1440-1703.12023

Pacifici, K., Reich, B. J., Miller, D. A., Gardner, B., Stauffer, G., Singh, S., McKerrow, A., and Collazo, J. A. (2017). Integrating multiple data sources in species distribution modeling: a framework for data fusion. *Ecology* **98**, 840–850. doi:10.1002/ecy.1710

Parrish, J. K., Burgess, H., Weltzin, J. F., Fortson, L., Wiggins, A., and Simmons, B. (2018). Exposing the science in citizen science: fitness to purpose and intentional design. *Integrative and Comparative Biology* **58**, 150–160.

Pearse, H. (2020). Deliberation, citizen science and covid-19. *The Political Quarterly* **91**, 571–577. doi:10.1111/1467-923X.12869

Piccolo, R. L., Warnken, J., Chauvenet, A. L. M., and Castley, J. G. (2020). Location biases in ecological research on Australian terrestrial reptiles. *Scientific Reports* **10**, 9691. doi:10.1038/s41598-020-66719-x

Pocock, M. J., Tweddle, J. C., Savage, J., Robinson, L. D., and Roy, H. E. (2017). The diversity and evolution of ecological and environmental citizen science. *PLoS One* **12**, e0172579. doi:10.1371/journal.pone.0172579

Pocock, M. J., Roy, H. E., August, T., Kuria, A., Barasa, F., Bett, J., Githiru, M., Kairo, J., Kimani, J., Kinuthia, W., and Kissui, B. (2019). Developing the global potential of citizen science: assessing opportunities that benefit people, society and the environment in East Africa. *Journal of Applied Ecology* **56**, 274–281. doi:10.1111/1365-2664.13279

Poisson, A. C., McCullough, I. M., Cheruvelil, K. S., Elliott, K. C., Latimore, J. A., and Soranno, P. A. (2020). Quantifying the contribution of citizen science to broad-scale ecological databases. *Frontiers in Ecology and the Environment* **18**, 19–26. doi:10.1002/fee.2128

Richart, C. H., Chichester, L. F., Boyer, B., and Pearce, T. A. (2019). Rediscovery of the southern California endemic American Keeled Slug *Anadenulus cockerelli* (Hemphill, 1890) after a 68-year hiatus. *Journal of Natural History* **53**, 1515–1531. doi:10.1080/00222933.2018.1447700

Richter, R. (2015). Rediscovery of the rare coccinellid *Micraspis flavovittata* (Crotch, 1874) in western Victoria (Coleoptera: Coccinellidae). *Australian Entomologist* **42**, 73.

Roberts, D. R., Bahn, V., Ciuti, S., Boyce, M. S., Elith, J., Guillera-Arroita, G., Hauenstein, S., Lahoz-Monfort, J. J., Schröder, B., Thuiller, W., and Warton, D. I. (2017). Cross-validation strategies for data with temporal, spatial, hierarchical, or phylogenetic structure. *Ecography* **40**, 913–929. doi:10.1111/ecog.02881

Rowley, J. J., Callaghan, C. T., Cutajar, T., Portway, C., Potter, K., Mahony, S., Trembath, D. F., Flemons, P., and Woods, A. (2019). FrogID: citizen scientists provide validated biodiversity data on frogs of Australia. *Herpetological Conservation and Biology* **14**, 155–170.

Roy-Dufresne, E., Saltré, F., Cooke, B. D., Mellin, C., Mutze, G., Cox, T., and Fordham, D. A. (2019). Modeling the distribution of a wide-ranging invasive species using the sampling efforts of expert and citizen scientists. *Ecology and Evolution* **9**, 11053–11063. doi:10.1002/ece3.5609

Sands, D. P. (2018). Important issues facing insect conservation in Australia: now and into the future. *Austral Entomology* **57**, 150–172. doi:10.1111/aen.12342

Schmidt-Lebuhn, A. N., Knerr, N. J., and González-Orozco, C. E. (2012). Distorted perception of the spatial distribution of plant diversity through uneven collecting efforts: the example of Asteraceae in Australia. *Journal of Biogeography* **39**, 2072–2080. doi:10.1111/j.1365-2699.2012.02756.x

Schubert, J. (2020). First records of *Maratus robinsoni* Otto & Hill 2012 and *Maratus vultus* Otto & Hill 2016 (Araneae: Salticidae: Euophryini: *Maratus* Karsch 1878) from Victoria, Australia. *Peckhamia* **206**, 1–7.

Silvertown, J., Harvey, M., Greenwood, R., Dodd, M., Rosewell, J., Rebelo, T., Ansine, J., and McConway, K. (2015). Crowdsourcing the identification of organisms: a case-study of iSpot. *ZooKeys* **480**, 125–146. doi:10.3897/zookeys.480.8803

Simmons, B. I., Balmford, A., Bladon, A. J., Christie, A. P., De Palma, A., Dicks, L. V., Gallego-Zamorano, J., Johnston, A., Martin, P. A., Purvis, A., and Rocha, R. (2019). Worldwide insect declines: an important message, but interpret with caution. *Ecology and Evolution* **9**, 3678–3680. doi:10.1002/ece3.5153

Skejo, J., Connors, M., Hendriksen, M., Lambert, N., Chong, G., McMaster, I., Monaghan, N., Rentz, D., Richter, R., Rose, K., and Franjević, D. (2020). Online social media tells a story of *Anaselina, Paraselina*, and *Selivinga* (Orthoptera, Tetrigidae), rare Australian pygmy grasshoppers. *ZooKeys* **948**, 107–119. doi:10.3897/zookeys.948.52910

Steven, R., Barnes, M., Garnett, S. T., Garrard, G., O’Connor, J., Oliver, J. L., Robinson, C., Tulloch, A., and Fuller, R. A. (2019). Aligning citizen science with best practice: threatened species conservation in Australia. *Conservation Science and Practice* **1**, e100. doi:10.1111/csp2.100

Taylor, G. S., Braby, M. F., Moir, M. L., Harvey, M. S., Sands, D. P., New, T. R., Kitching, R. L., McQuillan, P. B., Hogendoorn, K., Glatz, R. V., and Andren, M. (2018). Strategic national approach for improving the conservation management of insects and allied invertebrates in Australia. *Austral Entomology* **57**, 124–149. doi:10.1111/aen.12343

Troudet, J., Grandcolas, P., Blin, A., Vignes-Lebbe, R., and Legendre, F. (2017). Taxonomic bias in biodiversity data and societal preferences. *Scientific Reports* **7**, 9132. doi:10.1038/s41598-017-09084-6

Tulloch, A. I. T., Possingham, H. P., Joseph, L. N., Szabo, J., and Martin, T. G. (2013). Realising the full potential of citizen science monitoring programs. *Biological Conservation* **165**, 128–138. doi:10.1016/j.biocon.2013.05.025

Turak, E., Bush, A., Dela-Cruz, J., and Powell, M. (2020). Freshwater reptile persistence and conservation in cities: insights from species occurrence records. *Water (Basel)* **12**, 651. doi:10.3390/w12030651

Uyeda, K. A., Stow, D. A., and Richart, C. H. (2020). Assessment of volunteered geographic information for vegetation mapping. *Environmental Monitoring and Assessment* **192**, 554. doi:10.1007/s10661-020-08522-9

Vásquez-Restrepo, J. D., and Lapwong, Y. (2018). Confirming the presence of a fourth species of non-native house gecko of the genus *Hemidactylus* Oken, 1817 (Squamata, Gekkonidae) in Colombia. *Check List* **14**, 665. doi:10.15560/14.4.665

Vuong, Q. H. (2018). The (ir)rational consideration of the cost of science in transition economies. *Nature Human Behaviour* **2**, 5. doi:10.1038/s41562-017-0281-4

Wagner, D. L. (2020). Insect declines in the Anthropocene. *Annual Review of Entomology* **65**, 457–480. doi:10.1146/annurev-ento-011019-025151

Walker, K. (2014). BowerBird: a home for Australian citizen science. *Wildlife Australia* **51**, 34.

Wang, Y., Casajus, N., Buddle, C., Berteaux, D., and Larrivée, M. (2018). Predicting the distribution of poorly-documented species, Northern black widow (*Latrodectus variolus*) and Black purse-web spider (*Sphodros niger*), using museum specimens and citizen science data. *PLoS One* **13**, e0201094. doi:10.1371/journal.pone.0201094

Ward, M. S., Simmonds, J. S., Reside, A. E., Watson, J. E., Rhodes, J. R., Possingham, H. P., Trezise, J., Fletcher, R., File, L., and Taylor, M. (2019). Lots of loss with little scrutiny: the attrition of habitat critical for threatened species in Australia. *Conservation Science and Practice* **1**, e117. doi:10.1111/csp2.117

Wiggins, A., Newman, G., Stevenson, R. D., and Crowston, K. (2011). Mechanisms for data quality and validation in citizen science. In ‘2011 IEEE Seventh International Conference on e-Science Workshops’. pp. 14–19. (IEEE Computer Society: Washington, DC, USA.)

Williams, A., Althaus, F., Pogonoski, J., Osterhage, D., Gomon, M., Graham, K., Appleyard, S. A., Gledhill, D., Bray, D., McMillan, P., and Green, M. (2018). Composition, diversity and biogeographic affinities of the deep-sea (200–3000 m) fish assemblage in the Great Australian Bight, Australia. *Deep-sea Research. Part II, Topical Studies in Oceanography* **157–158**, 92–105. doi:10.1016/j.dsr2.2018.05.005

Wilson, J. S., Pan, A. D., General, D. E. M., and Koch, J. B. (2020). More eyes on the prize: an observation of a very rare, threatened species of Philippine Bumble bee, *Bombus irisanensis*, on iNaturalist and the importance of citizen science in conservation biology. *Journal of Insect Conservation* **24**, 727–729. doi:10.1007/s10841-020-00233-3

Woinarski, J. C., Russell-Smith, J., Andersen, A. N., and Brennan, K. (2009). Fire management and biodiversity of the western Arnhem Land Plateau. In 'Culture, Ecology and Economy of Fire Management in North Australian Savannas: Rekindling the Wurrk Tradition'. (Eds J. Russell-Smith, P. J. Whitehead, and P. M. Cooke.) pp. 201–228. (CSIRO Publishing: Melbourne, Vic., Australia.)

Wood, C., Sullivan, B., Iliff, M., Fink, D., and Kelling, S. (2011). eBird: engaging birders in science and conservation. *PLoS Biology* **9**, e1001220. doi:10.1371/journal.pbio.1001220

Young, B. E., Dodge, N., Hunt, P. D., Ormes, M., Schlesinger, M. D., and Shaw, H. Y. (2019). Using citizen science data to support conservation in environmental regulatory contexts. *Biological Conservation* **237**, 57–62. doi:10.1016/j.biocon.2019.06.016

Ziembicki, M. R., Woinarski, J. C., Webb, J. K., Vanderduys, E., Tuft, K., Smith, J., Ritchie, E. G., Reardon, T. B., Radford, I. J., Preece, N., and Perry, J. (2015). Stemming the tide: progress towards resolving the causes of decline and implementing management responses for the disappearing mammal fauna of northern Australia. *Therya* **6**, 169–226. doi:10.12933/therya-15-236

Handling Editor: Natasha Robinson