National Environmental Science Program

RESEARCH REPORT

31st May 2022

National Assessment of Climate-Driven Species Redistribution using Citizen Science Data

Barrett Wolfe, Shannon Kjeldsen, Jan Strugnell, Sue-Ann Watson, Gretta Pecl


Milestone number: 5, Research Plan number: 1.30

Please address inquiries to: Gretta Pecl, Gretta.Pecl@utas.edu.au

Preferred citation

Barrett Wolfe, Shannon Kjeldsen, Jan Strugnell, Sue-Ann Watson and Gretta Pecl (2022), National Assessment of Climate-Driven Species Redistribution using Citizen Science Data. Report to the National Environmental Science Program. University of Tasmania

Copyright

Acknowledgement

This work was undertaken for the Marine and Coastal Hub, a collaborative partnership supported through funding from the Australian Government's National Environmental Science Program (NESP). The NSW component was also supported by the NSW Marine Estate Management Strategy.

NESP Marine and Coastal Hub partners

The Australian Institute of Marine Science, Bioplatforms Australia, Bureau of Meteorology, Charles Darwin University, Central Queensland University, CSIRO, Deakin University, Edith Cowan University, Flinders University, Geoscience Australia, Griffith University, Integrated Marine Observing System, James Cook University, Macquarie University, Murdoch University, Museums Victoria, NSW Department of Planning and Environment (Environment, Energy and Science Group), NSW Department of Primary Industries, South Australian Research and Development Institute, The University of Adelaide, University of Melbourne, The University of Queensland, University of New South Wales, University of Technology Sydney, The University of Sydney, University of Western Australia, The University of Wollongong

Disclaimer

Cover images: features Redmap Australia sightings #3465 (Stephanie Garra) and #1624 (Derrick Cruz)

This report is available on the NESP Marine and Coastal Hub website: www.nespmarinecoastal.edu.au

Contents

List of figures

List of tables

Executive summary

This project developed state-based (WA, NSW and Tas) and national report cards assessing Australian marine species to determine species that have potentially undergone recent changes in distribution, extending their southern range limit into new areas as our oceans warm. These report cards draw upon several national citizen science databases and use a robust decision tree analysis to outline which species are shifting, and with what degree of certainty. Project objectives were to 1. draw upon the existing knowledge of marine citizen scientists to identify climate-driven changes within the Australian marine estate; and 2. develop products to communicate to and engage with the public on issues of climate change and biodiversity using their own citizen science information. The report cards can also be used to drive public interest in the NESP MAC Hub and in the status of biodiversity in Australia.

Where whole communities or ecosystems have been explored, estimates suggest that on average 50% of species globally are already responding to climate change by shifting geographic distribution. These changes in species distributions (or ranges) affect ecosystem structure and function, impact both fisheries and conservation, and often require specific management as species leave existing locations or enter new areas. A recently published systematic review of all published scientific literature on range shifts within Australian waters revealed at least 198 species shifting, but also substantial geographical and taxonomic gaps (Gervais et al 2021). This study also showed that 1/5th of the published studies incorporated citizen science information, demonstrating the huge contribution citizen science can make. However, many of the citizen science databases had not been systematically searched and analysed to formally assess species changes in distribution.

This current project collated and assessed out-of-range observations from:

- The Redmap (Range Extension Database and Mapping Project) Australia project, a national initiative since 2012 that invites fishers and divers to submit photographic observations specifically of out-of-range species with the explicit aim of identifying potential range extending species. https://www.redmap.org.au/
- The iNaturalist Australasian Fishes project that invites marine users to send in photographs of any marine species, regardless of location, and has amassed over 136,000 observations as of February 2022 (many designated as 'research grade' with a community consensus on a precise identification) that are yet to be analysed for potential range shifting species. https://inaturalist.ala.org.au/projects/australasian-fishes
- The Reef Life Survey project which undertakes structured systematic surveys of inshore reefs with trained volunteer SCUBA divers, providing a rich database of species occurrences through time that is used to assess a variety of biogeographic questions. https://reeflifesurvey.com/

Collectively, these programs represent a significant untapped resource that enabled assessment of potential changes in species distributions, and identification of particular regions or taxa that might require targeted research effort.

Using the Redmap Australia species list as a basis, 200 target species were included in this assessment. Geographic distribution limits for these species were established as of 2012 to define the historical southern boundary limit against which to compare subsequent out-of-range observations recorded between 2013 and 2021. After filtering the citizen science database extracts for target species and verification, the final species occurrence dataset included over 76,000 non-duplicate out-of-range observations, representing 197 of the 200 target species. Of the target species considered for the assessment, 77 were represented in the databases with observations with photographic evidence beyond the established historical distribution limits.

82 potential regional range extensions were assessed in total as some of the 77 species had observed out-of-range observations on either both the west and east coasts, or both southward in Tasmania and west on the south coast. Relatively even numbers of range extensions were assessed in Western Australia, New South Wales, and Tasmania with smaller numbers in Queensland, Victoria and South Australia. Western Australia, New South Wales and Tasmania all had sufficient range extensions determined to warrant state-specific report cards and all shifts were then reported in the national poster summarising all changes in distribution.

The target list of species assessed included a wide range of taxonomic groups, including anemones, corals, crabs, lobsters, seastars, urchins, sharks, rays, dolphins, morays, octopus and many different teleost fish. In total, 31 range extensions were classified with high confidence, eight with medium confidence, and 43 with low confidence. The mean extent of range extensions assessed, calculated as latitudinal distance (or longitudinal distance on the south coast), from historical distribution limit to the maximum extent of recent citizen science observations or was 316 km, with a maximum of 1474 km. The eight extensions with the greatest poleward extent all occurred from the Leeuwin current-influenced west.

Engagement from citizen scientists, marine managers and others marine stakeholders throughout both the development of the assessment process and the design and review of the report cards was extremely high. The near-final draft of the report cards have been widely disseminated so far and have been very positively received. Over the next year the final products will be used by the citizen science programs involved, host and supporting institutes, coastal councils, and local and state-based fishing, diving, marine tourism and conservation groups to engage people on issues related to climate change and biodiversity generally, and the climate-driven redistribution of life specifically. The national report card was designed as a visually appealing poster that can be readable from A3 format (ie the size a standard office printer could print colour copies) but also high resolution enough to maintain quality at A0. Through extensive online networking and social media, we hope that the poster will be widely distributed, printed and displayed on office walls and halls around Australia.

1. Introduction

Approximately half of all studied plants and animals globally, on land and in the ocean, are moving poleward or, on land, to higher altitudes to find conditions they can survive and thrive in as the climate around them changes (IPCC 2022). In marine systems, these changes in species distribution are, in general, occurring faster in regions that are warming more quickly (Poloczanska et al 2016). Moreover, climate-driven changes in species distribution are already having serious consequences for economic development, livelihoods, food security, human health, and culture. In some cases, changes in distribution are even influencing the pace of climate change itself, producing feedbacks to the climate system (Pecl et al 2017).

Since 1970, on average our oceans have warmed by 1-2 °C and are 26-30% more acidic (IPCC 2019). Changes in atmospheric conditions have also driven major shifts in the eddies, currents and upwellings of the oceans (Martinez-Moreno et al. 2021), and marine heatwaves have increased in frequency, duration and intensity (Laufkötter et al. 2020). However, there is large geographical variation in the rates of change in these parameters and processes, particularly around the Australian coastline. For example, the south-east of Australia is a 'warming hotspot', warming at almost four times the global average and in the top 10% for rates of ocean warming globally (Hobday and Pecl 2014), primarily due to a strengthening of the East Australian Current (EAC, Oliver et al. 2015). It is also a region that has experienced several marine heatwaves in recent years (Holbrook et al. 2019), with peak intensities 1.5 – 3°C degrees above the long-term climatology in the Tasman Sea in 2015/2016, 2017/2018 and 2018/19 (Oliver et al. 2021). Likewise, waters around south-west Australia are warming at almost three times the global average and are also in the top 10% for rates of warming globally (Hobday and Pecl 2014). Similarly, south-west Australian waters have also experienced strong marine heatwaves (Holbrook et al 2019).

Associated with increases in temperatures around the Australian coastline, many changes in the distribution of species have been reported, both range contractions at the warmer range edges and range extensions at the cooler range edges. At the warmer equatorward range edges of a species' distribution, thermal conditions may exceed species' limits such that physiological and behavioural performance declines, leading to local extinction events and range contractions. In contrast, range extensions at cooler poleward range edges represent species arriving, settling and ultimately surviving under conditions that progressively favour increased performance (Bates et al 2014).

A recent systematic review demonstrated that since 2003, at least 198 Australian marine species have undergone permanent long-term shifts in their geographic distributions (Gervais et al. 2021). These redistributions are strongly associated with ocean warming, with 87.3% of shifts (173 species) polewards in direction and therefore aligning with expectations under warming trends. However, changes in distribution are also linked to extreme climate events such as El Niño, and with marine heatwave events that have also facilitated the contraction of warmer range limits and extension of cooler poleward range limits of species in Australia (Babcock et al. 2019). The Gervais et al review also highlighted that the number of marine species undergoing range shifts reviewed was almost certainly a considerable underestimate due to limited standardised monitoring around the coastline and considerable spatial and taxonomic bias. They also suggested that although the ideal data to document changes in species distributions are rigorous, structured surveys repeated over time, and these should be facilitated wherever possible, ‘perfect is the enemy of good’ and many useful insights can be generated by careful compilations of varied data – such as data collected from citizen science sources.

Whilst many changes in species distribution may not have any discernible ecological or socioeconomic effects, in some cases, redistributing species have ecological implications similar to invasive or pest species, altering native ecosystems and processes. The climate-driven redistribution of species can therefore have economic and sociological ramifications, including implications for Indigenous, commercial and recreational fisheries, as well as conservation and human health (Pecl et al., 2017). For example, within the last 40 years, range-extending sea urchin (*Centrostephanus rodgersii*) have shifted poleward from New South Wales to Tasmania resulting in macroalgal loss due to overgrazing, causing an estimated minimum net loss of ~150 macroalgae-associated species (Ling and Keane 2018). However, at the moment, it is difficult to discern ahead of time which changes in distribution are likely to require further research and/or management attention, and which ones will not. Additionally, we have very little knowledge about the net effect of many species changing distributions all at the same time, i.e. multiple species leaving and entering a given region at the same time, meaning many new links between species will be created and old links will be broken (Marzloff et al 2016).

The potential implications of range shifting species for resource management are important to consider (Melbourne-Thomas et al 2021), and moreover, many stakeholder groups are already starting to adapt autonomously to these changes (Pecl et al 2019a). However, these autonomous adaptations by marine-dependent people and industries are generally ‘reactive’ forms of adaptation, and the development of anticipatory or planned strategies for managing range shifting species is needed (Scheffers and Pecl 2019). As a starting point for increasing capacity to understand, predict and manage for range-shifting species, we need to improve our existing approaches for detecting changes in the distribution of species around the Australian coastline (Gervais et al 2021).

Although there are many changes in distribution being reported, there is limited systematic surveying and subsequent analysis to observe and assess range shifts (Gervais et al 2021). However, citizen-science programs have provided high-quality evidence and consensus of reported range extensions (Robinson et al 2015, Stuart-Smith et al 2017) via repeated observations of species beyond the limits of their historical distributions. By engaging fishers, divers and other marine users in active documentation of potential species responses to climate change, citizen science programs can also help engage marine communities on issues related to climate change using their own data (Nursey-Bray et al 2017, Kelly et al 2019). Nonetheless, the information being logged and recorded via citizen science programs needs to be collated and formally assessed to evaluate what species are shifting, or potentially shifting. In isolation, single observations of species on their own cannot be conclusive of species range shifts. Instead, patterns over time need to be examined, with consideration of the certainty with which historical range limits of the given species were known.

Here, we review, collate and assess out of range observations of marine species from citizen science projects operating at a National scale around the Australian coastline. Briefly, the broad objectives of this report are to:

1. Provide an assessment of potential changes in species distributions for key species within Australia's EEZ
2. Provide an early indication of species or regions that are priority areas for targeted scientific research. Although this assessment will focus on range extensions only, regions with high rates of range extension may indicate regions that could/should be assessed further for range contractions via further targeted study.
3. Provide a demonstration of the value of citizen science
4. Create a range of outputs to engage with the broader public on climate change, using their own information

2. Methods

To assess the evidence available regarding range extensions of marine species around the Australian coastline we collated observations from Australian citizen science programs, undertook extensive quality control and verification of the data collated, determined historical poleward range limits of the relevant species and then examined evidence for recent range extensions beyond those range limits using a methodology modified from Robinson et al 2015.

2.1 Overview of marine species occurrence citizen science data sources

2.1.1 Redmap Australia

Redmap invites members of the public to submit unusual marine species sightings with photographic evidence through a web site interface (redmap.org.au) or smartphone application. Users can use regional target species lists or submit sighting data for any marine species they consider unusual in a given area. Submitted records are verified by a relevant taxon expert to verify the species ID and sighting information (e.g., geolocation, body size). The Redmap database contains citizen science observations collected from Tasmania since late 2009; from New South Wales, South Australia, Western Australia, Victoria and Queensland since late 2012, although Queensland has only been promoted properly in recent years. The Redmap Australia project is described in full in a recent peer-reviewed publication (Pecl et al 2019b). Validated observations were exported from the database for assessment on February 20, 2022.

2.1.2 iNaturalist

Similar to Redmap, iNaturalist accepts species observations with photographs from the public. However, all biological observations are invited and included, as opposed to only unusual or out-of-range marine species sightings as with Redmap. Another key difference from Redmap is taxonomic identifications of iNaturalist observations are decided through a crowd-sourcing mechanism. Species observations are considered ‘verifiable’ if they include a date, geolocation, photograph and are wild (not cultivated/in captivity). All registered users can submit identification guesses for an observation, and when at least two-thirds of at least two identifiers agree on a taxon identification of a verifiable observation, the observation receives a ‘research grade’ rating. As such, not all ‘research grade’ iNaturalist observations will have undergone expert verification, necessitating an additional verification process (described below). Within the broader iNaturalist platform are discrete ‘projects’ that curate observations within specific location/taxonomic criteria, for example the ‘Australasian Fishes Project’. Initiated in October 2016 by Mark McGrouther of the Australian Museum. Australasian Fishes facilitates collection of observations of fishes in the Australia/New Zealand (and nearby nations) exclusive economic zones. Data was exported from the Australasian Fishes Project within the area bounded by 45°–9°S, 110°E–160°E on February 20, 2022, which included approximately 136,000 observations. For non-fish species on the assessment list (i.e., not within the scope of Australasian Fishes Project), relevant data were extracted with targeted queries by species name.

2.1.3 Reef Life Survey

Reef Life Survey is a marine life monitoring program. Unlike iNaturalist and Redmap, Reef Life Survey collects species occurrences observed during survey SCUBA dives conducted with standardised methodology by a collaboration of professional scientists and citizen scientists that have undergone a rigorous training process. As such, species are identified by trained and assessed divers *in situ* and photographic evidence is not systematically collected and associated with the data. Since Reef Life Survey data can't be verified by photographic evidence as per the other data sources, they were only included in the assessment in a corroborative role (see Table 1). Reef Life Survey data were obtained from the Australian Ocean Data Network (https://portal.aodn.org.au/) on January 25, 2022, as follows. The Reef Life Survey global reef fish abundance and biomass, cryptobenthic fish abundance, off-transect species observations, and mobile macroinvertebrate abundance datasets were extracted with the bounding box 45°–9°S, 110°E–160°E, and non-Reef Life Survey data ('program' = ATRC or Parks Vic) were removed, leaving 629,000 species observations (excluding duplicate species within a single survey dive). At the time of data extract the most recent survey dive date was Jan. 29, 2021.

2.2 Species list

Redmap Australia maintains a list of 'target' species suspected of undergoing geographic redistributions related to oceanic warming (see https://www.redmap.org.au/species/). As part of the listing process, the historical distributions of each species were established from scientific literature and references (see Pecl et al 2019b). Most of these species were listed on the Redmap website in December 2012, with a small number of additions since such as recently described species (e.g., the coral *Pocillopora aliciae*), and several species of interest for Queensland in 2017. This 'pre-registered' Redmap target species list serves as the basis for the current assessment. In addition, 20 species that had historical distribution limits established (via the same process as for Redmap listed above) as part of a recent study that utilised Redmap data (García Molinos et al., in review) were also included in this assessment. Finally, four other species which are pending Redmap listing were also included (*Acanthocybium solandri*, *Argonauta argo, Trygonoptera imitata, Pseudolabrus biserialis*). In total, the target species list contained 200 species (Appendix A), including two cnidarians, seven crustaceans, 16 elasmobranchs, four marine mammals, five molluscs, three reptiles, and 159 bony fish.

2.3 Assessment methodology

The methodology used for assessment was adapted from the approach developed by Robinson et al. (2015), used in production of a Tasmanian report card on range shifts https://www.redmap.org.au/article/the-redmap-tasmania-report-card/. This method was based on a qualitative decision tree framework developed for the rapid assessment of potential range extensions of Tasmanian marine species by a 21-member working group in 2012. Briefly, the assessment produces estimates of overall confidence in potential range extension by combining classifications of confidence in A) a species historical distribution limits at a given time point and B) evidence of observations of post-recruits further south of the poleward historical range limit, provided by citizen science observation data (Figure 1). In cases where species have not been detected in multiple years (or if not highly mobile, were not detected during winter), detectability determines the final strength of evidence estimate classification (Figure 1B). Highly mobile species include highly migratory and pelagic species, and other species for which there is evidence of migration on the regional scale in the scientific literature. High detectability is determined by abundance (Low = patchy or rare; High = common) and/or conspicuousness (Low if at least two of the following apply: < 30 cm body size, camouflage, hiding behaviour; otherwise High) being High, unless a species is only encountered by fishers, then detectability is based solely on abundance. Abundance data was mined from Reef Life Survey species pages (https://reeflifesurvey.com/species/search.php) and other species-specific reference material, and size data was extracted from FishBase.

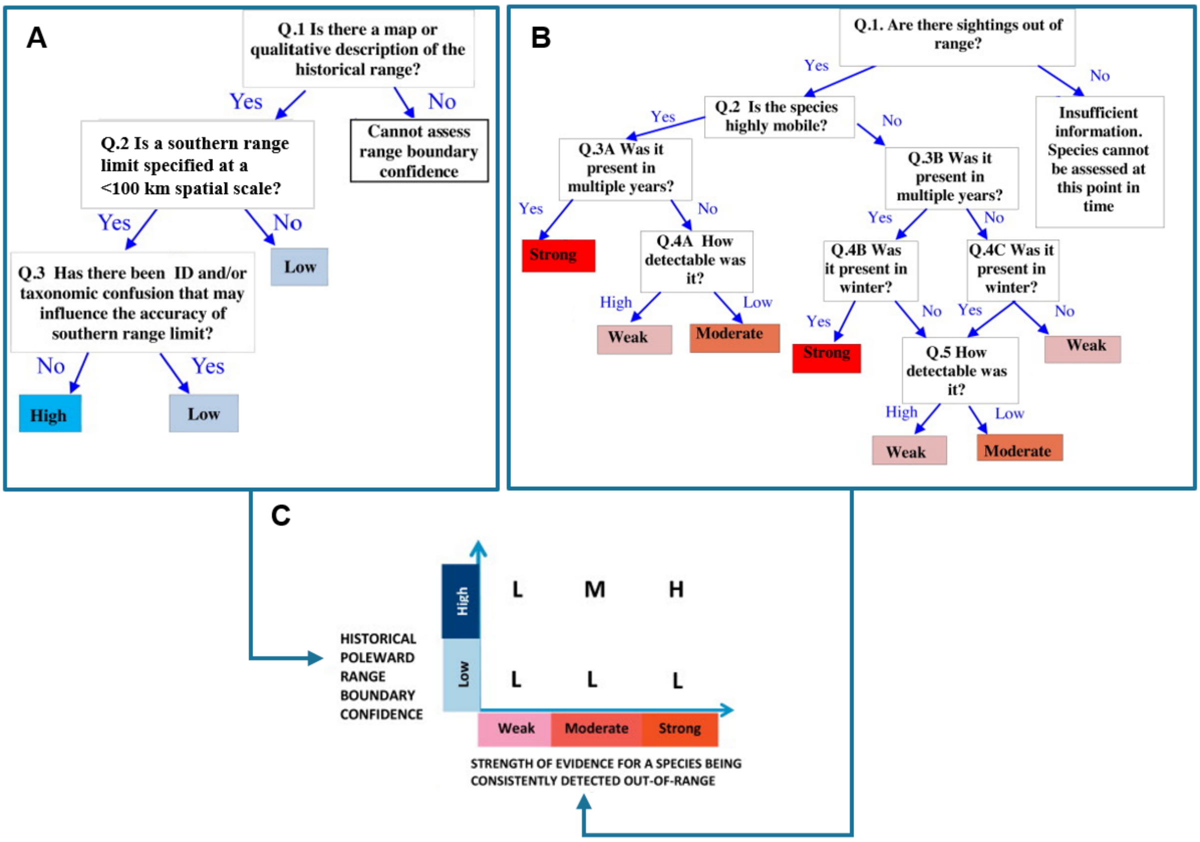

Figure 1. Overview of the original Robinson et al. (2015) rapid species range extension assessment decision tree methodology. For each assessed species, decision trees classify confidence in historical poleward range boundaries (**A**) and strength of evidence provided by extralimital detections (**B**). These classifications are then combined to provide an estimate of overall confidence in a potential range extension (**C**).

2.3.1 Workshop process to refine assessment methodology

A series of workshops were convened beginning in November 2021 to consider refinements or improvements to the Robinson et al 2015 methodology. These considerations included 1/ any new information emerging from the rapidly developing field of climate-driven species redistribution ecology (Bonebrake et al 2018), 2/ any changes necessary to adapt the methods from the original geographic context of Tasmania only to Australia-wide, and 3/ ensuring appropriateness of the method for the full taxonomic range of species considered in the current assessment.

Workshops were conducted online and in-person over the October-December 2021 period. Attendees included representatives from NSW DPI, NRE Tasmania, DPIRD WA, dive and fishing club representatives, and representatives from all the major citizen science programs included in this assessment. Climate change and/or biodiversity experts from University of Tasmania, Newcastle University, James Cook University, Museum of North Queensland, and the Australian Museum also participated. The lead author of the original assessment method (Lucy Robinson, CSIRO), contributed to discussions via email.

The outcome of this series of workshops, including changes to the assessment method considered and modifications adopted, are described in Table 1.

Table 1: Modifications to the Robinson et al. 2015 approach considered in the workshop process and outcomes

Modification considered	Outcome
Change 'winter' criteria, Q4 (Fig. 1B): As observations during winter are weighted as stronger evidence of a range extension, as they may reflect evidence of overwintering in new range areas, changing from meteorlogical winter (June 1st–August 31st) to the period reflecting annual minimums should make the criteria more ecologically relevant.	*Modification adopted.* As there is evidence of a delay between overwinter mortality of extralimital vagrants and onset of seasonal minimum temperatures (Figueira et al. 2009), the consecutive three months with the least minimum average minimum monthly temperature (based on long-term sea surface temperature data*) and the month following were adopted as winter criteria. QLD, NSW, VIC, TAS: July–October SA: August–November WA: September–December
Include temporal component (e.g., month of detection) for highly migratory species: Recent research has demonstrated that seasonal occurrence of some migratory species (including Redmap target species) at high latitudes has been increasing (Champion et al. 2018) or is forecasted to increase (Niella et al. 2022). Considering this criterion may yield insights into the phenological aspect of range extensions.	*Not adopted.* After a review of distributional information available for migratory target species, it was concluded that the seasonality of distributional extent was not high enough resolution to assess phenological extensions with confidence.

Modification considered	Outcome
Generalise the "southern range limit" distributional criteria to include regional expectations under climate velocity: Range extensions may not always be reflected to the south (or in latitudinal extent). For example, due to the influence of the Leeuwin current, which transports warm water around Australia's southwest toward the Great Australia Bight, warming-driven range extensions in the region would primarily be expected to occur from west to east (or even southwest to northeast).	*Modification adopted.* To make the Robinson et al. 2015 methodology relevant for assessment of marine species Australia-wide (which was focused on the east coast of Tasmania), southern latitudinal distributional limits were considered along the east and west coasts, along with longitudinal distributional limits (e.g. eastern or western extents) on the south coast.
Remove Question 2 from the historical distribution confidence decision tree: In the Robinson et al. (2015) method, if there is not a regional (<100 km) scale limit specified (e.g. distribution only described to state level), distribution confidence is estimated as "Low" and the species is assessed.	*Modification adopted.* If regional-scale distributional information was not available, the most conservative interpretation (i.e., that which yields the greatest historical distribution extent) was made when translating to maximum latitude or longitude to decrease likelihood of 'false positives' and obviating the need to downgrade distribution confidence estimates (In practice, finer scale information was available for virtually all species assessed).
Change the outcome of "No" to Question 3 on historical distribution decision tree: Where taxonomic or identification uncertainty could lead to spurious results enough to reduce distribution limit confidence to "Low", do not assess species	*Modification adopted.*
Add a 20 km 'buffer' to historical distributional limits when assessing if observations are out of range: The buffer is intended to decrease the likelihood of spurious results arising from imprecise descriptions of distribution limits.	*Modification adopted.*

Modification considered	Outcome
Consider life stage of species observations separately (*e.g. juvenile vs adult) in the decision tree framework:* As the presence of adults *vs* juveniles can provide different evidence of occurrence in a new range area, considering life stage explicitly may provide greater resolution of the available evidence of range extensions.	*Modification partially adopted.* In practice, historical distributions were found to reflect the same life stages that occur in recent observations (e.g., for tropical reef fishes like *Naso unicornis* on the east coast, for which out of range observations were all juveniles, historical distributions were found to similarly reflect the maximum extent of newly recruited juveniles (Fowler et al. 2017), thus obviating the need to consider evidence provided by different life stages separately. Life stage was not generally well enough resolved in distribution references to treat range extensions of adults separately. However, the resolution was available for several species with historical distribution limits in Tasmania (Last et al. 2011), for which adults have a historically more constrained distribution than juveniles, thus out-of-range sightings of adults were assessed separately for these species.
Incorporation of non-Redmap citizen science data	iNaturalist observations are treated the same as Redmap observations if photographic evidence has been verified by an expert. Reef Life Survey data (no photographic evidence) are only incorporated in a corroborative role, for example to provide secondary evidence of winter or multi-year observations up to the geographical extent that photographic evidence of species occurrence is available. Species that were only detected out of range by Reef Life Survey observations were thus not included in the assessment.

* https://www.seatemperature.org/australia-pacific/australia

2.4 Citizen science species occurrence data and quality control/verification

Species observations were obtained from three citizen science-based programs: Redmap Australia, Reef Life Survey, and iNaturalist, as described above in section 2.1. Finally, the species list was cross-checked against Eye on the Reef data (courtesy of GBRMPA), a Great Barrier Reef-specific citizen science monitoring project, however no records of target species occurred beyond expected historical distribution limits. Duplicates were removed by filtering the data from the three sources for observations at the same coordinates on the same date of the same species. Spurious records (e.g., dubious location) from iNaturalist and Reef Life Survey were screened for by examining maps of the data in consultation with representatives from each program (Mark McGrouther and Rick Stuart-Smith, respectively).

A process to ensure expert verification of iNaturalist observations was implemented as follows. First, an R script was used to query the iNaturalist API (https://api.inaturalist.org/v1/) for the identifiers of out-of-range target species observations, and the user names of the (286 total) users that had made at least one identification was extracted. With the project curator Mark McGrouther, a list of these users known to be species experts (professional biologists, taxonomists, etc.) was developed. Then, observations which had already been identified by an expert were confirmed, and then observations which had not yet been verified by an expert were flagged for review by a relevant expert, either within the iNaturalist framework or externally, and the sightings which could be confirmed were then included in the assessment.

2.5 Assessment of species historical distributions

While all Redmap 'target' list species had historical geographic distribution limits established as when listed as described above, prior to assessment, the known distributions as of 2012 of all species for which observation data was available were reassessed. Reassessment served two main purposes. Firstly, species that were on the original Redmap list (e.g., all species in the Bass Strait/Tasmania region) had historical distributions assessed in 2009, rather than 2012 for the majority of the current species. Second, the availability and accessibility of ecological data has increased considerably, with more historical datasets becoming publicly available and added to centralised databases. Historical species records are sometimes revised or newly emerge (e.g., identification of museum specimens), resulting in flux in species' known distributions over time. Reassessment ensured that all available distributional data sources were incorporated and reflected any revisions to known distributions since 2012, and that all historical distributions were determined via a standardised and repeatable method.

Key sources for the species distribution 'reassessment' included Australian Faunal Directory (AFD, ABRS 2009) and Atlas of Living Australia (ALA), along with key regional distribution references and species checklists. The Australian National Expert Fish Distribution polygons (https://researchdata.edu.au/australian-national-fish-expert-distributions/671428) for each species were consulted as well as these were produced circa 2012. However, they were not used as a definitive distribution reference as where polygons reflect the extent of observation data (versus modelled habitat beyond the geographic extent of occurrence data) could not be discerned for many species. From each species' AFD page (e.g., https://biodiversity.org.au/afd/Genus_species), the 'Extra Distribution Information' sections (which provide a description of distribution limit reference points around Australia and date of the species' page's last update was extracted and the distribution description was converted to latitudinal and longitudinal extent. Where AFD distributions were of greater poleward (i.e., southern, or longitudinal on the south coast) geographical extent than the original Redmap distributions, and AFD pages were last updated prior to 2013, the assessed species distributions were expanded accordingly. In cases of broader distributions reported from AFD pages for species from 2013 onward, the expanded distribution limit was noted, and the distribution references listed by the species' AFD page were consulted along with other sources of occurrence data to identify whether evidence of occurrence in the expanded range existed prior to 2013. The ALA Spatial Portal (https://spatial.ala.org.au) was used to search for georeferenced occurrence records that would expand distributions poleward, from various data sources from 2012 or prior, for each species. Data sources queried through ALA include

Online Zoological Collections of Australian Museums, CSIRO trawl surveys and historic fishing data. Individual extralimital records were verified by pursuing the occurrence metadata, and where possible the data source material and/or contacting relevant personnel for verification. For commercially harvested species, catch data was consulted through Status of Australian Fish Stocks reports (https://www.fish.gov.au/) and Bureau of Rural Science Commercial Fisheries Presence 2000—2002 dataset. Finally, citizen science observations from iNaturalist or Redmap made prior to 2012 were also incorporated in reassessed species 'historical' distributions.

2.6 Development of the report cards

Within the workshop process, the original (2013) Tasmania Report Card (https://www.redmap.org.au/article/the-redmap-tasmania-report-card/), was reviewed by collaborators as a starting point for design of the new state and national report cards (Figure 2), and a list of desired design features was developed, which included:

- A single design for the three state-based report cards that is effective both in print (A3 leaflet) and on-screen single-page versions: the original design was optimised for viewing in print form with information spanning the centrefold of the middle two pages. However, it was noted that relative to a decade ago when the original was released, readers are more likely to view the report card on a screen with one page displayed at a time, so each page should be comprehendible as a stand-alone.
- A map component with a visual representation of the range extensions that had been assessed.
- Larger pictures of species
- To communicate the scientific value of participation in citizen science programs, detailed information about the citizen scientists who made out-of-range observations, such as how many of each type of observer (divers, fishers, beachcombers, etc.), total number of observers, etc.
- Technical details (i.e., of the decision tree analysis framework used) to be exported to a supporting information section to focus the actual report card on key messages.
- A QR code to a dedicated page hosted on the Redmap website that contains supporting information (technical details and methodology), educational resources, and outlines ways to participate in the citizen science programs.
- For the National report card, a design that is effective as a poster that could be printed out as A2-A0. If possible (depending on the number of total range extensions assessed), the poster would be legible down to an A3 size, as this is the maximum size paper workplace printers can print.
- For the state-based report cards, an introduction section linking ocean warming and local climatic change to ecological changes observed by community members, followed by several examples of range extending species described in narrative form.
- An invitation to participate in the non-Redmap programs used in the assessment (Reef Life Survey and iNaturalist) to encourage citizen science engagement beyond the specialist (i.e., on range extension) focus of Redmap.

The resulting draft report card, after internal revisions, then underwent a testing process (section 3.3).

Back page (Left) and Front page (Right)

Pages 2 and 3, open as a centrefold

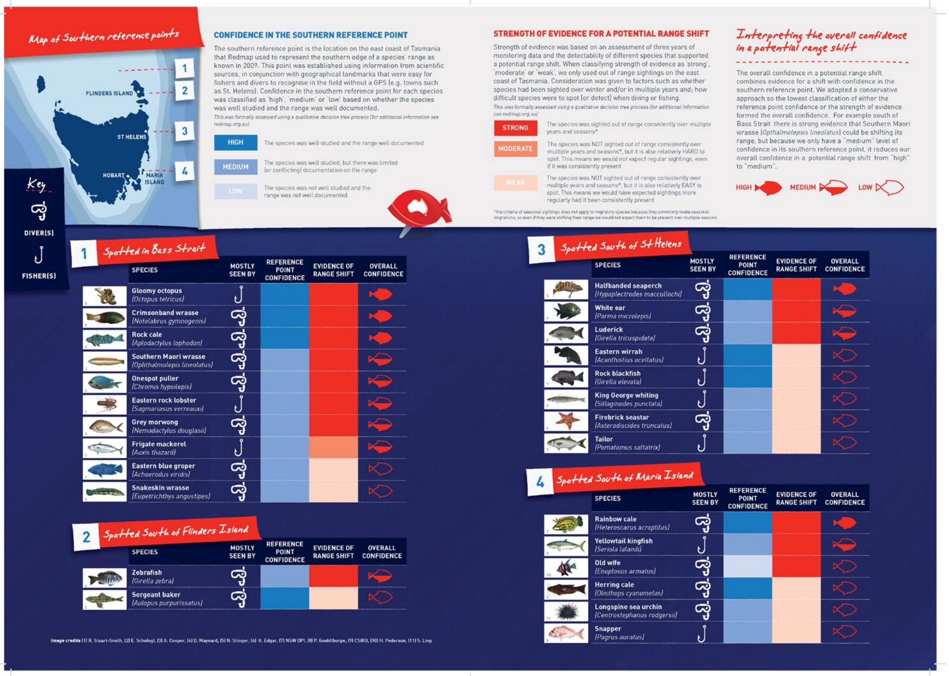

Figure 2: The original Redmap Range Shift Report Card (2013)

3. Results

3.1 Citizen science species observations and distribution assessments

After filtering the citizen science database extracts for target species and verification, the final species occurrence dataset included over 76,000 non-duplicate out-of-range observations, representing 197 of the 200 target species (Table 2). The three species that were not represented in the observation data were Tropical Sawshark (*Pristiophorus delicatus*), Freshwater Sawfish (*Pristis pristis*), and Mozambique Seabream (*Wattsia mossambica*). While the number of species present in each database was similar, the generalist databases Reef Life Survey and iNaturalist had much greater total numbers of observations than Redmap, reflecting the latter's specialist focus.

Of the 197 species that had observations and thus the possibility for assessment, distributions were assessed without evidence of taxonomic or identification uncertainty that would impact confidence in the historical distribution boundaries, with the exception of Little Bellowsfish (*Macroramphosus gracilis*), for which the taxonomic relationship with putative congener *M. scolopax* (which has a greater distributional extent) is unclear and thus the species was removed from consideration. Of the 196 remaining target species considered for the assessment, 77 were represented in the databases with observations with photographic evidence beyond historical distribution limits (Table 2).

Table 2. Citizen science observations of target species.

	Redmap	Reef Life Survey	iNaturalist	Total (unique)
Target species represented	151	156	175	197
Total observations of target species	1069	68854	28570	76118
Median observations per species	4	136	69	215
Out-of-range target species represented*	69	22	45	77
Out-of-range observations	229	320	371	914
Median out-of-range obs. per species	2	5	2	3.5

*Only including species with photographic evidence out of range, i.e., represented in the Redmap or iNaturalist databases

While the generalist databases (Reef Life Survey and iNaturalist) had much more extensive coverage of species occurrence in general compared to Redmap, representation of 'out-of-range' observations were more similar across databases, with a total of 914 non-duplicate observations. While Redmap yielded less observations compared to the other databases, Redmap data provided the most extensive representation of out-of-range target species by a wide margin (69 of the 77 total). Several other species were putative represented out-of-range by Reef Life Survey data, e.g., *Chaetodon melannotus* and *Parupeneus ciliatus* which are not included in the total of 77 assessed. However, these species featured on the Report Card products in "Have You Spotted and Photographed these species" sections (e.g., Appendix C.)

3.2 Potential range extension confidence assessment

Of the 77 species assessed, 82 potential regional range extensions were assessed, with several species observed out-of-range on either both the west and east coasts, or both southward in Tasmania and west on the south coast. Relatively even numbers of range extensions were assessed in Western Australia, New South Wales, and Tasmania with smaller numbers in Queensland, Victoria and South Australia (Table 3). Western Australia, New South Wales and Tasmania all had sufficient range extensions determined to warrant state-specific report cards (Appendix C, D and E respectively), and all shifts were then reported in the national poster summarising all changes in distribution (Appendix F). In total, 31 range extensions were classified with high confidence, eight with medium confidence, and 43 with low confidence.

Table 3. Assessed confidence estimates of potential range extensions by state.

	Confidence assessment			
State	High	Medium	Low	Total
NSW	11	3	10	24
QLD	0	0	5	5
SA	1	0	5	6
TAS	10	2	8	20
VIC	1	2	5	8
WA	9	2	13	24
Total (unique)	31	8	43	82

The mean extent of range extensions assessed, calculated as latitudinal distance (or longitudinal distance on the south coast), from historical distribution limit to the maximum extent of recent citizen science observations was 316 km, with a maximum of 1474 km (Table 4). The eight extensions with the greatest poleward extent all occurred from the Leeuwin current-influenced west (Figure 3).

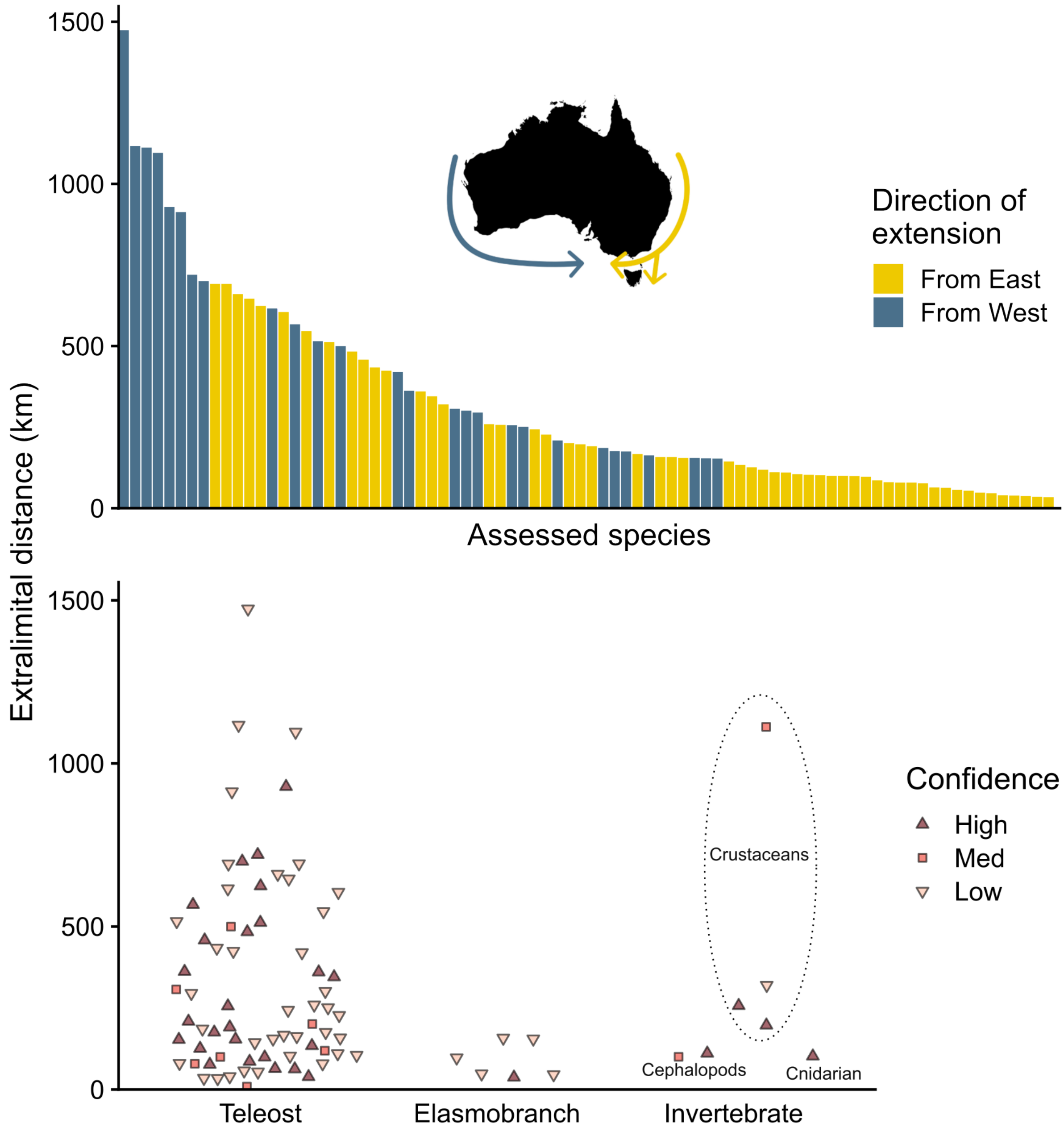

Figure 3. Extralimital distance (distance from historical distribution boundary to the maximum extent of recent citizen science observations, in kilometres) for each assessed regional potential range extension. Separate regional extensions of a single species (e.g. shifts on both WA and the east coast) are treated separately. **A)** Distance of the 82 assessed extensions by direction, "From East" indicates extensions on the east coast, or from east to west on the south coast. "From West" includes those originating on the west coast and extensions from west to east on the south coast.

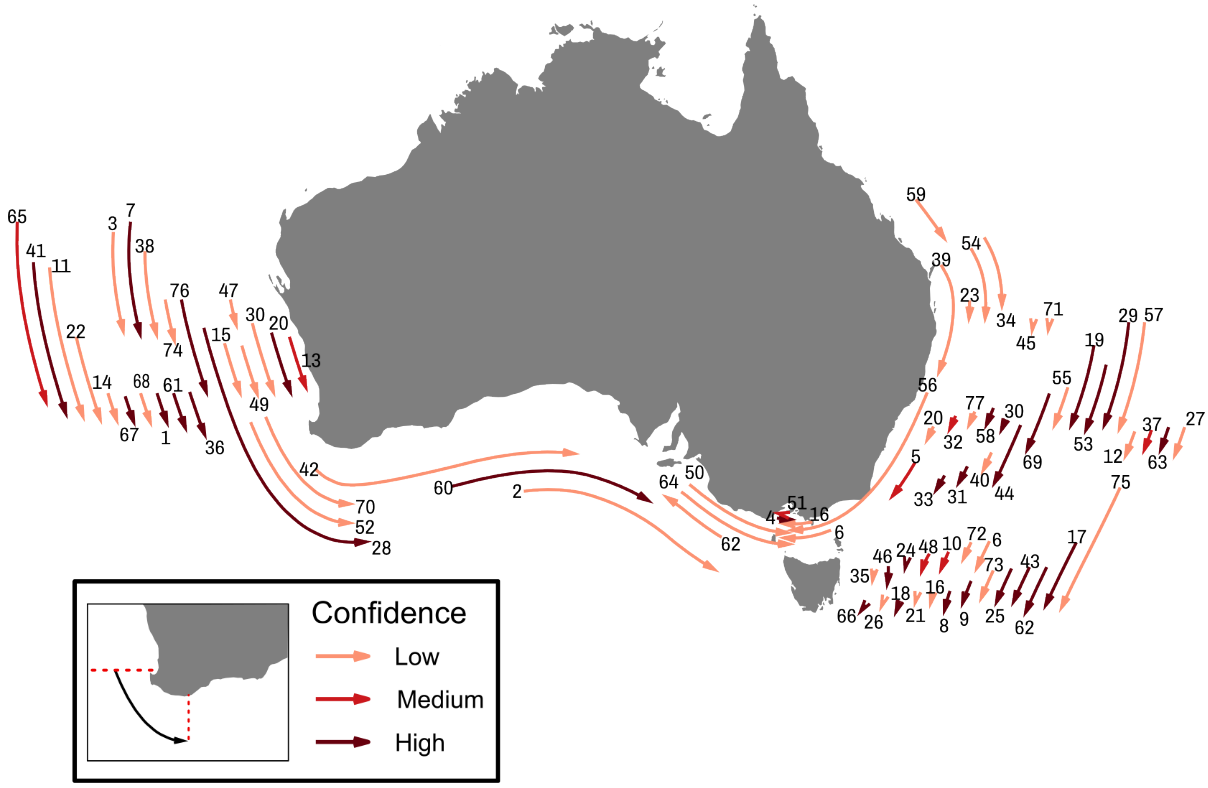

Figure 4. Graphical representation of 82 assessed range extensions. Numbers correspond to species' numbers in Table 4. The beginning (i.e., without arrowhead) of each extension line represents the latitude, or on the south coast, longitude, of the species' historical distribution limit in the region. The extent of the arrow depicts the maximum extralimital extent of recent citizen science observations. The arrows are spaced vertically to allow differentiation of lines and do not represent distance from the coast.

Table 4. Results of the rapid range extension assessment. Species numbers (#) correspond to those in Figure 4. Potential range extensions are presented separately for species with out-of-range data from multiple regions. Historical distribution limits in degrees latitude are southernmost distribution limits, while those in degrees longitude are western-most distribution limits, unless presented in italics (eastern-most limits). Extensions with confidence estimates denoted with "a" pertain to only adult life stages extending into areas where previously only juveniles were known to occur.

#	Species name	State	Confidence in range extension	Historical distribution limit	New extent	Distance (km)
1	*Abudefduf vaigiensis*	WA	High	32° 05' S	33° 40' S	176
2	*Acanthocybium solandri*	SA	Low	*128° 15' E*	140° 17' E	1096
3	*Albula argentea*	WA	Low	23° 09' S	28° 41' S	616
4	*Anoplocapros lenticularis*	VIC	High	144° 09' E	145° 02' E	77
5	*Antennarius striatus*	NSW/VIC	Med	35° 47' S	37° 35' S	201

6	*Aplodactylus lophodon*	TAS	Low	39° 57' S	41° 21' S	155
		VIC	Low	147° 36' E	144° 39' E	259
7	*Aprion virescens*	WA	High	22° 34' S	28° 51' S	700
8	*Argonauta argo*	TAS	High	42° 31' S	43° 31' S	111
9	*Arotrolepis filicauda*	TAS	High	42° 00' S	43° 08' S	126
10	*Auxis thazard*	TAS	Med	40° 30' S	41° 24' S	100
11	*Carangoides chrysophrys*	WA	Low	25° 08' S	33° 21' S	913
12	*Caranx ignobilis*	NSW	Low	34° 09' S	35° 27' S	144
13	*Centropyge tibicen*	WA	Med	29° 00' S	31° 45' S	307
14	*Chaetodon auriga*	WA	Low	32° 05' S	33° 33' S	163
15	*Chaetodontoplus personifer*	WA	Low	29° 21' S	32° 03' S	301
16	*Chromis hypsilepis*	TAS	Low	42° 39' S	43° 08' S	54
		VIC	Low	146° 24' E	144° 36' E	158
17	*Coryphaena hippurus*	TAS	High	40° 01' S	43° 14' S	360
18	*Dactylophora nigricans*	TAS	High	42° 60' S	43° 34' S	64
19	*Dascyllus reticulatus*	NSW	High	29° 28' S	33° 48' S	483
20	*Diploprion bifasciatum*	NSW	Low	33° 53' S	34° 36' S	79
		WA	High	28° 46' S	32° 01' S	362
21	*Enoplosus armatus*	TAS	Low[a]	42° 45' S	43° 07' S	40
22	*Epinephelus multinotatus*	WA	Low	29° 00' S	33° 30' S	500
23	*Epinephelus tukula*	QLD	Low	26° 59' S	27° 58' S	110
24	*Galeocerdo cuvier*	TAS	High	41° 00' S	41° 21' S	38
25	*Girella elevata*	TAS	High[a]	41° 22' S	43° 05' S	191
26	*Girella tricuspidata*	TAS	Low	42° 59' S	43° 18' S	35
27	*Glaucosoma scapulare*	NSW	Low	33° 55' S	35° 25' S	167
28	*Grammatorcynus bicarinatus*	WA	High	28° 30' S	118° 11' E	720
29	*Gymnosarda unicolor*	NSW	High	28° 12' S	33° 48' S	624
30	*Gymnothorax eurostus*	NSW	High	33° 30' S	34° 04' S	63
		WA	Low	28° 15' S	32° 01' S	420
31	*Heterodontus galeatus*	NSW	High	36° 01' S	36° 54' S	99
32	*Hippocampus histrix*	NSW	Med	33° 19' S	34° 01' S	79
33	*Hyporthodus ergastularius*	NSW	High	36° 30' S	37° 16' S	86
34	*Lates calcarifer*	QLD	Low	23° 28' S	27° 16' S	424
35	*Latropiscis purpurissatus*	TAS	Low	41° 28' S	41° 58' S	57
36	*Lethrinus miniatus*	WA	High	32° 01' S	34° 19' S	256
37	*Lethrinus nebulosus*	NSW	High	34° 04' S	35° 08' S	119
38	*Lutjanus argentimaculatus*	WA	Low	24° 14' S	28° 52' S	515
39	*Lutjanus johnii*	QLD/NSW	Low	25° 00' S	30° 56' S	660
40	*Lutjanus quinquelineatus*	NSW	Low	35° 16' S	36° 13' S	105
41	*Lutjanus sebae*	WA	High	24° 51' S	33° 12' S	929
42	*Makaira nigricans*	WA/SA	Low	*115° 15' E*	131° 26' E	1474
43	*Melicertus plebejus*	TAS	High	41° 17' S	43° 04' S	197
44	*Naso unicornis*	NSW	High	33° 48' S	36° 54' S	345
45	*Negaprion acutidens*	NSW	Low	28° 12' S	28° 38' S	48
46	*Nemadactylus douglasii*	TAS	High[a]	41° 14' S	42° 10' S	103
47	*Neotrygon australiae*	WA	Low	26° 56' S	28° 20' S	155
48	*Octopus tetricus*	TAS	Med	40° 36' S	41° 30' S	100
49	*Parachaetodon ocellatus*	WA	Low	29° 29' S	32° 08' S	295

50	*Parapercis ramsayi*	SA/VIC	Med	138° 36' E	144° 49' E	546
51	*Parma microlepis*	VIC	Low	144° 36' E	144° 12' E	34
52	*Parupeneus spilurus*	WA	Low	33° 39' S	117° 14' E	153
53	*Pentapodus paradiseus*	NSW	High	30° 31' S	35° 07' S	512
54	*Plectorhinchus lineatus*	QLD	Low	24° 04' S	27° 58' S	434
55	*Plectroglyphidodon dickii*	NSW	Low	31° 46' S	33° 48' S	227
56	*Plectropomus laevis*	VIC	Low	31° 56' S	145° 07' E	692
57	*Plectropomus leopardus*	NSW	Low	28° 12' S	33° 60' S	646
58	*Pocillopora aliciae*	NSW	High	32° 53' S	33° 48' S	102
59	*Premnas biaculeatus*	QLD	Low	21° 19' S	23° 30' S	243
60	*Pseudolabrus biserialis*	SA	High	*123° 47' E*	136° 03' E	1117
61	*Pterois volitans*	WA	High	32° 05' S	33° 58' S	209
62	*Sagmariasus verreauxi*	SA	Low	140° 42' E	137° 11' E	320
		TAS	High	41° 17' S	43° 36' S	257
63	*Scarus ghobban*	NSW	High	33° 55' S	35° 07' S	134
64	*Scorpis georgiana*	SA/VIC	Low	138° 06' E	144° 59' E	605
65	*Scylla serrata*	WA	Med	22° 34' S	32° 34' S	1112
66	*Seriola lalandi*	TAS	High	43° 12' S	43° 33' S	39
67	*Siganus fuscescens*	WA	High	32° 15' S	33° 38' S	154
68	*Stethojulis bandanensis*	WA	Low	32° 05' S	33° 40' S	175
69	*Thalassoma lutescens*	NSW	High	32° 06' S	36° 13' S	458
70	*Trachinotus botla*	WA	Low	33° 22' S	117° 19' E	186
71	*Triaenodon obesus*	NSW	Low	28° 12' S	28° 37' S	46
72	*Trygonoptera imitata*	TAS	Low	40° 00' S	40° 52' S	97
73	*Trygonorrhina dumerilii*	TAS	Low	41° 28' S	42° 53' S	158
74	*Variola louti*	WA	Low	26° 56' S	29° 11' S	251
75	*Xiphasia setifer*	NSW/Tas	Low	37° 06' S	43° 21' S	692
76	*Zanclus cornutus*	WA	High	26° 56' S	32° 02' S	567
77	*Zebrasoma scopas*	NSW	Low	33° 05' S	33° 48' S	80

3.3 Report Card design and testing

The draft report cards were sent to a variety of stakeholders for review, inviting feedback on overall design, text, graphics, symbols, colours, placement of different elements. 'Testers' included 20 citizen scientists that had submitted out-of-range observations that featured in the assessment through either Redmap or iNaturalist, dive clubs, state managers (and education and communication specialists), and feedback was discussed among collaborators and incorporated in subsequent drafts. Included here are near final versions of NSW (Appendix D), WA (Appendix C) and Tasmania (Appendix E) report cards which undertook nine, four and three rounds of revision respectively. As NSW was the first report card drafted it underwent more extensive revisions and subsequent changes as the 'test' card. Report cards for WA and Tasmania then incorporated all the relevant changes from the WA card testing and revisions, leading to less adjustments being necessary for those cards.

Feedback on the draft report cards was largely very positive, and we received feedback from most people contacted, indicating a high level of engagement from contributors and end-users. In addition to many relatively minor suggestions regarding colours, text, symbols etc, key constructive suggestions from several citizen scientists included using IMCRA bioregions versus MEOW ecoregions on the map, as these bioregions names held more meaning for local people. Citizen scientists also suggested including pictures of juvenile life stages where those will be the relevant life stages citizen scientists might encounter and where they appear significantly different from adult stages.

In addition to seeking feedback and review from the citizen scientists that contributed data to the report cards, we also received many constructive improvements from fisheries researchers, marine estate managers, communication experts from natural resource agencies and museums, recreational fishing engagement officers and dive clubs. The project team also presented the draft report cards to a group from DAWE on May 26, with a high degree of interest and engagement and positive feedback, including the suggestion that such an analysis could/should be repeated at regular intervals or even made into an online semi-automated report card that could feed into State-of-the-Environment reporting and other relevant environmental assessments. Lastly, the NSW DPI communications team also assessed the state-based report cards for accessibility and made suggestions to ensure the online pdf documents can be read and accessed by people with disabilities, primarily for the vision-impaired that may use assistive technology to read the file through text-to-speech or a Braille printout.

The National report card poster (Appendix F) included here is the first draft produced and is undergoing review and revision now. We anticipate quite a few changes to the poster including:

- Reducing clutter, especially at the top and in and around the central map
- Swapping the placement and prominence of headline statement and the Redmap logo so that the headline 'What's on the move around Australia' is more prominent and the Redmap logo is much smaller.
- The pencil near the 'more ways to be a citizen scientist' text is replaced with a camera icon.
- The information in the four boxed sections (confidence box, legend, citizen science program info, observer details) is incorporated more seamlessly with other elements of the poster so it does not look 'piecey'.

3.4 Completed and planned dissemination of report cards

The Redmap project had already gathered scientific evidence to support proof of concept as i) an effective early indication of changes in species distribution (i.e. species range shifts; shifts - Fogarty et al 2010; Robinson et al. 2015), and ii) a successful mechanism for community engagement that has improved understanding of marine environmental issues, including climate change (Nursey-Bray et al 2017, Pecl et al 2019b). The report cards generated here can be used as communication devices to help engage the broader public on marine climate change specifically and biodiversity generally, as well as the work and activity of the NESP MAC Hub and of the many opportunities that exist to participate in citizen science.

Significant awareness of the report cards has already been created through the extensive engagement with citizen scientists and end users throughout the assessment, design and review process, as described in earlier sections. Additional dissemination of the report cards thus far has included:

- Invited presentation by Gretta Pecl (IMAS) at the Volvo Ocean Lovers Festival, on April 24th, at Bondi Beach. The talk was titled 'Dive into citizen science' and featured the NSW report card and information on how to get involved in Redmap, iNaturalist and Reef Life Survey.

- Invited presentation and panel Q & A participation at the Blue Water Summit, held on Oceans Day July 8 and streamed live. The presentation by Gretta Pecl was titled "Citizen science to explore impacts of climate change" and included a description of the NSW report card and information on how citizen science observations from fishers and divers around the country and helping us understand the impacts of climate change. The recording for the whole summit is available here https://youtu.be/YNiWgUS4ghI. Following this presentation several fishing, diving and tourism groups made contact via the Redmap email address and requested printed materials be sent to them to help drive interest in their local area and group.

- Troy Gaston (University of Newcastle) presented a talk at the NSW Coastal Conference on May 31st, at Kingscliff, NSW. His talk was called "A citizen science-based assessment of marine species redistributions in New South Wales". Afterwards, several coastal councils (Central Coast Council, South East Local Land Service and Tweed Shire Council) indicated they would like some Redmap signage put up around local fishing spots, and were interested in hard copies of the report card to disseminate.

- John Keane UTAS Dive Club) presented the draft Tasmanian report card at the Tasmanian Combined Dive Clubs Weekend in July, to several hundred SCUBA divers.

- Barrett Wolfe (IMAS) will be presenting the suite of report cards and the assessment methods at an accepted presentation at the AMSA conference in Cairns in August 2022. His presentation is entitled "A citizen science-driven assessment of marine species redistributions around Australia".

- Joshua Brown (WA DPIRD) will be presenting a talk entitled "A citizen science-based assessment of marine species redistributions in Western Australia" based on the WA report card at the State NRM & Coastal Conference 2022 in September.

- An article based around the national report card is being pitched to The Conversation (similarly themed articles have been successful in the past, eg https://theconversation.com/how-you-can-help-scientists-track-how-marine-life-reacts-to-climate-change-33370).

Further ongoing engagement and dissemination will also occur via Redmap, iNaturalist, Reef Life Survey and the various research partner institute avenues. These will include the respective Facebook, Twitter and Instagram pages, as well as online newsletters produced and distributed by some of these programs and organisations. The report cards will also be printed and made available at various events over the coming months and years including Agfest in Tasmania as well as several marine/ocean, boat, fishing and diving festivals and exhibits, and the next international *Species on the Move* conference in Florida in May 2023.

Lastly, there is some permanent signage planned along the NSW coast in popular fishing and diving spots to help raise awareness of marine citizen science programs, including the apps that can be downloaded and where to find the results or outcomes of marine citizen science observations. The QR code to the report card will be added to this signage.

Potential outcomes of disseminating the report cards with the broader community include:

- **Inspire** fishers, divers, boaters and the public to log uncommon marine sightings
- **Value** the community’s marine observations, knowledge and experience
- **Engage** the public with marine warming concepts through participation in citizen science
- **Attract** an online community to the program and institute websites, apps, and social media
- **Present** citizen science and climate-related data in an easy-to-read style
- **Encourage** monitoring of changes in the distribution of marine species in Australia’s vast seas
- **Collect** observations of uncommon species from fishers, divers and the public
- **Strengthen** collaboration between marine citizen science programs
- **Engage** marine scientists in collaborations with coastal communities

4. Conclusions

The oceans have absorbed approximately 90% of the additional heat trapped in the atmosphere and 25% of the additional carbon emitted (IPCC 2019) – without this 'service' the impacts of climate change around the world would be much more severe. However, the associated physical and ecological changes in Australian coasts and oceans have been substantial, with major implications for marine systems. Changes in species distributions and the composition of ecological communities are one of the most pervasive responses to climate-driven warming as equatorward limits become too warm for survival for many species and new habitats at poleward limits become warm enough to survive in (Pecl et al. 2017). There is, however, great taxonomic and regional variation in the pace and magnitude of these shifts in species distributions, or 'range shifts', and highly variable ecological and socio-economic implications.

This project explored evidence provided by citizen science observations for potential range extensions in a target species list of 200 species, including two cnidarians, seven crustaceans, 16 elasmobranchs, four marine mammals, five molluscs, three reptiles, and 159 bony fish. Systematic reassessment of historical distribution limits for all species of as 2012 ensured that all historical distributions were determined via a standardised and repeatable method. Of the 200 species on the initial list, observations were found for 197, however, one species was removed from the list due to taxonomic uncertainty. Of the196 remaining target species considered for this assessment, 77 were represented in the databases with photographic observations beyond the reassessed historical distribution limits. Of those 77 species, several had observed out-of-range observations on either both the west and east coasts, or both southward in Tasmania and west on the south coast, leading to 82 assessed shifts. Relatively even numbers of range extensions were assessed in Western Australia, New South Wales, and Tasmania with smaller numbers in Queensland, Victoria and South Australia. In total, 31 range extensions were classified with high confidence, eight with medium confidence, and 43 with low confidence. The mean extent of range extensions was 316 km, with a maximum of 1474 km.

Importantly, the vast majority of the likely range extensions documented here are additional to those already reported in the Gervais et al 2021 systematic review of published literature on range shifts around the Australian coastline, highlighting the value of observations reported by the public. Furthermore, there were some interesting differences between the two key studies. Gervais et al (2021) revealed a much higher number of shifts in Tasmania, compared to WA or eastern Australia (Figure 5), which was suggested to be partly a function of research effort (Fogarty et al 2019). However, in the current study, there were relatively similar numbers of range extensions reported in Tasmania, WA and NSW (Table 3). Moreover, in Gervais et al (2021), rates of range extension appeared to be greater in species along the eastern coast, but in our study, the extralimital distances reported were generally greater on the western coast (Figure 3). However, caution is advised in direct comparisons between the two studies as the methodologies are not directly comparable.

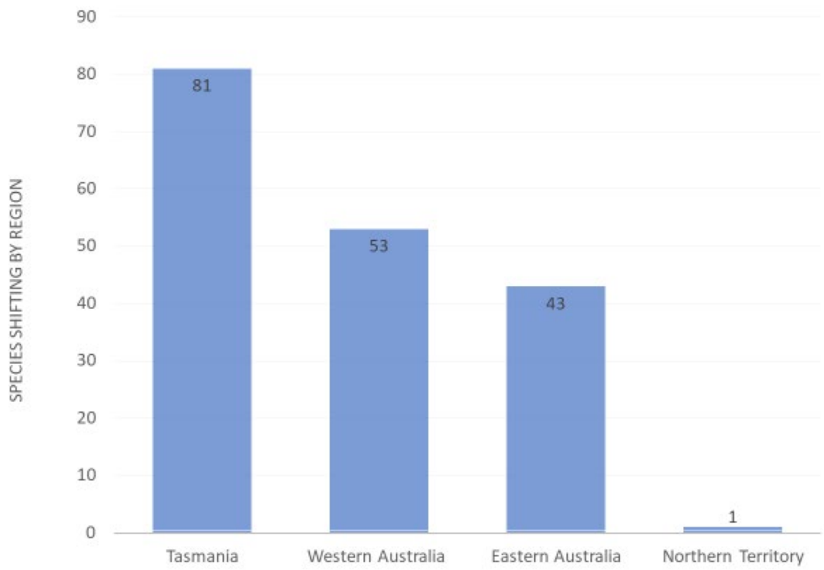

Figure 5: Numbers of range shifts recorded per region as reported in the Gervais et al 2021 systematic review of published literature. Note, 'Eastern Australia' refers mostly to NSW but includes a few shifts at the bottom of QLD and the top of Victoria.

While the Leeuwin current is generally not as strong or fast as the East Australian Current, the eight longest extralimital distances reported here (recorded away from the historical range boundary limits of species) were recorded on the west coast, and the east coast recorded a greater number of shorter extralimital distances. This could reflect a number of issues, including differences in the seasonal patterns of the currents, with the Leeuwin current weakest in summer and the EAC strongest in summer. The Leeuwin current is also positioned more on the edge of the continental shelf and bathes the Abrolhos and Rottnest islands in tropical water even though they are medium and high latitude, creating warm water refuges further south where some of the likely changes in range limits start or finish. The Leeuwin is the world's longest coastal current and the heat the current transfers to southern Australia makes it hospitable to marine species normally found much closer to the equator. Differences between the respective coastlines in the likely extensions we report here may also be related to the occurrence data availability along each of the coasts and the density of citizen science observers.

Whilst this study was designed to assess the evidence for species range extensions, based on available citizen science data, the assessment process has provided some additional unexpected outcomes. For example, through our extensive data verification and quality control process, multiple inaccuracies in historical biodiversity records were identified and corrected. Two *Plectropomus leopardus* (Sydney 1882) records submitted by the Australian Museum and reported at out-of-range locations were subsequently identified as *Acanthistius ocellatus* (eastern wirrah, records A.13690, A.13691). Another example, among others, is a *Lutjanus johnii* specimen from 1987 held in the ANFC national fish collection that was correctly identified as *L. malabaricus.* These examples highlight the need for caution when using large ecological and biodiversity databases, and the need for careful data cleaning, verification and quality control. Another issue of potential importance, depending on the nature of the study, is the lack of other accompanying data. OZCAM (Online Zoological Collections of Australian Museums) provides access to an online database of records aggregated from faunal collections databases in Australian museums, and uploads records to OBIS/GBIF/ALA but does not necessarily distinguish between larvae vs adults. For example, the southernmost records of *Aprion virescens* (green jobfish) from central and southern NSW, as recorded in ALA, are all larvae and thus not relevant for assessing the post-recruit distribution. However, there is no indication of life stage in the associated record data (but we confirmed this via tracing the original details provided by Australian Museum). There were similar issues with iNaturalist data which gets uploaded to biodiversity databases when the observations are designated as 'research grade', but our verification process found several duplicates and obvious misidentifications.

Citizen science records can be influential in assessing how species distributions are changing over time with climate change, but they can also be useful for conducting historical range redescriptions from historical citizen science records. For example, Valerie Taylor's images from the early 1970s have been uploaded to iNaturalist, including Midnight Snapper *Macolor macularis* from Heron Island, yet this species was not noted from the Capricorn group in the later Russell 1983 and Russell 1990 checklists and so these historical sightings substantially redefine the range (https://www.inaturalist.org/observations/40804713). Establishing historical range limits was a significant challenge for the current study, even for some of the more common species. It is the lack of a systematically established distributional limit that prevented more species being included in the assessment here. Australia has an estimated 48,000 marine animal species (Butler et al 2010) but without accurate and consistent baseline information it becomes very challenging to assess any future changes in the distributions of most of these species.

By altering food webs, competing for habitat with existing species, or other species interactions, some species shifting into new regions will result in ecosystem disturbance (Ling 2008, Bonebrake et al 2018). However, it is difficult to predict which shifting species may create challenges, and we don't yet know much about the net effect of many species shifting at the same time within a given region (Marzloff et al. 2016, Bonebrake et al. 2018). The potential ecosystem implications of shifting species are largely unknown, especially for regions like the east coast of Tasmania, NSW and WA where many species are shifting all at the same time. Potential implications of range shifting species for resource management is important to consider, especially as many stakeholder groups are already starting to adapt autonomously to the changes (Pecl et al. 2019a). In Tasmania, charter operators are advertising trips for 'new' species, fishers have made changes to product handling and landing practices, and aquaculture operators have changed farming operations (Pecl et al. 2019a). Assessment of key biological and ecological parameters of range shifting species, particularly in new areas of the range extensions, is of critical importance to underpin comprehensive understanding of species characteristics at the extending range edge (Wolfe et al 2020), what novel species interactions may be occurring, and how 'new' species may be fitting into the changing ecosystem (Smith et al 2022, Twiname et al 2019).

Several of the species likely to be undergoing range shifts included species popular with the recreational sector but also important components of commercial fisheries in multiple states. Thus, their increasing presence in waters further south may be providing new fishing opportunities for recreational and commercial fishers. However, in most cases it is currently unclear as to whether these species have or are likely to become established as self-sustaining populations in those range extension areas, or simply persist as spill-over from their endemic range areas. If the former is the case, it will be important to consider population attributes such as age structure, growth, mortality, and reproduction relevant to the populations in the range extension areas, when developing and refining management strategies to sustainably manage and maximize the opportunities these 'new' species bring. In addition, the broader ecosystem impacts of such range extending species, including competition with resident species at similar trophic levels, or increased predation to lower trophic levels are unknown but could have consequences for other recreationally and commercially important species and/or ecosystem function. Understanding these interactions will have benefits for the assessment and management of natural marine resources more generally, ensuring fisheries continue to thrive under climate change.

Given the pervasive but highly variable nature of range shifts, and the high number of people observing and documenting wildlife daily, the potential for citizen scientists to play an effective role in the early detection of range shifting species, specifically range extensions, is substantial (García Molinos et al., in review). Moreover, the value of citizen science approaches is not limited to providing quality cost-effective data, as they also hold great potential to improve climate change communication and engagement with the public (Nursey-Bray et al 2017, Pecl et al 2019b). Furthermore, studies based on the Redmap project show that participation in citizen science can allow users to display their marine citizenship and shared concern about the marine environment, and that this can allow them to earn trust from other user groups, with positive implications for marine and coastal management (Kelly et al 2019). Based on the enthusiastic response to our invitation to citizen scientists that contributed data used in the report cards here to provide feedback on the card content and design, citizen scientists are excited to see their observations being used and being useful. Such interest should help drive dissemination of the final repot card products, especially given that almost 500 citizen scientists have contributed data used in the report cards, along with almost 100 scientists verifying their data.

Observations of species outside of their known range are increasing and the ‘gold standard’ to document these comprehensively would be structured scientific surveys that covered a wide range of habitats (inshore, mid and deeper waters). To complement structured scientific surveys, citizen-science programs – that have to date underpinned one-fifth of range shift reports and are able to cover large spatial scales – can help address some critical data gaps and at the same time create community interest and awareness in climate change. However, these programs also need longer-term and sufficient funding to operate in order to be successful. It is critical to consider that extensive species redistributions are projected to occur around the Australian coastline for the foreseeable future. We need to ensure that the appropriate mechanisms are in place to assess changes in biodiversity over time accurately, across all key habitats and regions, so that communities, industries and resource managers can be prepared to adapt to climate-driven changes in Australian marine systems in the most constructive way possible.

5. Recommendations

1. In the context of understanding climate-driven species redistributions in the marine systems of Australia, citizen science projects provide valuable, unique and highly complementary data to traditional scientific sources. However, in order to maintain these benefits, or indeed achieve their full potential, citizen science projects need appropriate financial and institutional support.

2. Here, we generated a subset of 200 species based around those that were originally identified as potentially range shifting, via the Redmap project. Reassessing the historical range limits of these 200 species using a systematic and consistent approach took considerable effort. Australia has around 48,000 marine animal species, many of which would be considered data poor and so presumably assessing range limits for these species is likely to be difficult or associated with a high degree of uncertainty. Nonetheless, given the ongoing and indeed likely escalating nature of species redistribution, the distributions of a much larger group of species needs to be systematically assessed so that we have consistent baselines from which to measure future change.

3. Given the pace of likely shifts reported here and elsewhere over the last 7-10 years, a decadal or even five yearly review of range shifts of a larger group of species, would be highly recommended. An alternative approach may consider the development of a semi-automated online report card which regularly harvests available data and updates an online version of the approach taken here (noting that historical baselines would need formal evaluation for all species considered beforehand, as indicated above).

4. Range shifts from the respective report cards could be useful inputs into State-of-the-Environment reporting, and the report cards themselves could be considered as an action under the UN Decade of Ocean Science for Sustainability (we are applying for this).

5. Given millions of Australians go fishing or diving every year, and more still participate in marine tourism, or activities on the beach, there is considerable potential for growth of marine citizen science. Previous studies have clearly shown considerable potential for growth in volunteer recruitment, and that this can contribute constructively to scientific and public knowledge of the marine environment (Martin et al 2016a).

6. This study provides further strong evidence of the pervasive nature of climate-driven species redistribution, and of the concentration of shifts along our south west and south east sections of the Australian coastline. Predictive modelling and an exploration of the mechanisms that drive or limit species distribution are needed, along with an understanding of the ecosystem level implications of multiple losses and gains of species from the one region.

7. While this project has been successful in determining a level of baseline information for range shifting species, mainly around the south east and south west regions, ongoing monitoring is necessary. For ecologically, culturally or socio-economically important species it would be recommended to also assess potential changes to age/size structure, recruitment variability, and areas of potential spawning/recruitment. This is important to

allow for development and implementation of proactive (rather than reactive) strategies to sustainably manage shifting species, including for emerging fisheries.

8. Ongoing monitoring would require continued engagement with the citizen science community. Redmap is particularly successful in identifying out-of-range observations, and in raising awareness surrounding a new species in a new environment (Pecl et al 2019b). However, interest/engagement wavers once the novelty wears off, or knowledge surrounding this species becomes commonplace. Therefore, collaborating and working alongside programs where data collection is more routine, such as the 'Tassie Fish Frame Collection Program', is useful for sustained engagement and data collection of those species which are known to be in the new location but for which data is still limited (i.e., Snapper, King George Whiting, Yellowtail Kingfish in southern Tasmania). This is an example of where complementarity between citizen science initiatives can improve the quality and scope of data collection of range extending species.

9. An online hub/central source for all marine citizen science programs would be useful for the general public to engage and provide information irrespective of their interests or abilities (i.e., photography, diving, fishing, education, clean-ups). Such a central hub would not only reach a wider audience but allow for different institutions/initiatives to collaborate and identify gaps within their own program which could be supplemented within programs elsewhere. Cross-pollination across different citizen science initiatives provides the opportunity to share resources, and ultimately maximizes community outreach and data collection efforts (Gabra-Landry et al 2022).

10. Lastly feedback is important to increase, or even retain, engagement with the fishing and diving community. Research has demonstrated that it is essential for citizen science programs to effectively and regularly communicate with the existing participants, to regularly keep participants informed of the data that they have provided to not only increase scientific awareness, but also foster a sense of community and purpose amongst participants (Martin et al 2016b, Kelly et al 2017, Nursey-Bray et al 2018).

6. Acknowledgements

We acknowledge the hundreds of citizen scientists of Australia – recreational fishers, SCUBA divers, beach combers, snorkellers, boaters, spear fishers and marine naturalists – that generously contribute their time and knowledge to help document important changes around the coastline. Likewise, almost 100 scientists from 30+ institutions across Australia kindly provide their expertise and time to verify observations submitted. Citizen science projects typically operate on lower levels of funding and survive through substantial inkind support. Redmap Australia, Reef Life Survey and iNaturalist for example, also receive substantial help from a wide range of other contributors and volunteers which we would also like to acknowledge.

Many scientists, managers and science communicators provided essential input into the development of the assessment methodology and the presentation of results in report card formats. These included staff from NSW DPI, NRE Tasmania, DPIRD WA, dive and fishing club representatives, iNaturalist Australasian Fishes, Reef Life Survey, University of Tasmania, Newcastle University, James Cook University, Tasmanian Climate Change Office, Museum of North Queensland, and the Australian Museum.

Many citizen scientist observers also provided feedback on the design of the report cards, and we are grateful for their thoughtful improvements on the way we presented their data. Lastly, ecological monitoring often requires information over extended periods of time and so we would like to acknowledge the previous funders of the citizen science programs providing data used in this assessment.

7. References

ABRS 2009. Australian Faunal Directory. Australian Biological Resources Study, Canberra. Viewed 12 June 2022. http://www.environment.gov.au/biodiversity/abrs/online-resources/fauna/afd/index.html

Babcock RC, Bustamante RH, Fulton EA, Fulton DJ, Haywood MDE, Hobday AJ, Kenyon R, Matear RJ, Plagányi EE, Richardson AJ, Vanderklift MA (2019) Severe continental-scale impacts of climate change are happening now: Extreme climate events impact marine habitat forming communities along 45% of Australia's coast. Frontiers in Marine Science, 6.

Babcock R. C., Pillans R. D., Rochester W. A. (2017) Environmental and individual effects on the behaviour and spawning movements of *Lethrinus nebulosus* on a coral reef. Marine and Freshwater Research 68, 1422-1437.

Bates AE, Pecl GT, Frusher S, Hobday AJ, Wernberg T, Smale DA, Sunday JM, Hill NA, Dulvy NK, Colwell RK, Holbrook NJ, Fulton EA, Slawinski D, Feng M, Edgar GJ, Radford BT, Thompson PA, Watson RA (2014) Defining and observing stages of climate-mediated range shifts in marine systems. Global Environmental Change-Human and Policy Dimensions, 26, 27–38.

Bonebrake TC, Brown CJ, Bell JD, Blanchard JL, Chauvenet A, Champion C, Chen I-C, Clark TD, Colwell RK, Danielsen F, Dell AI, Donelson JM, Evengård B, Ferrier S, Frusher S, Garcia RA, Griffis RB, Hobday AJ, Jarzyna MA, Lee E, Lenoir J, Linnetved H, Martin VY, McCormack PC, McDonald J, McDonald-Madden E, Mitchell N, Mustonen T, Pandolfi JM, Pettorelli N, Possingham H, Pulsifer P, Reynolds M, Scheffers BR, Sorte CJB, Strugnell JM, Tuanmu M-N, Twiname S, Vergés A, Villanueva C, Wapstra E, Wernberg T, Pecl GT (2018) Managing consequences of climate-driven species redistribution requires integration of ecology, conservation and social science. Biological Reviews (Cambridge), 93, 284–305.

Butler AJ, Rees T, Beesley P, Bax NJ (2010) Marine Biodiversity in the Australian Region. PLoS ONE 5(8): e11831. https://doi.org/10.1371/journal.pone.0011831

Champion C, Hobday AJ., Zhang X, Pecl GT., Tracey SR. (2018) Changing windows of opportunity: past and future climate-driven shifts in temporal persistence of kingfish (*Seriola lalandi*) oceanographic habitat within south-eastern Australian bioregions. Marine and Freshwater Research 70, 33-42.

Fogarty, H. E., Burrows, M. T., Pecl, G. T., Robinson, L. M., Poloczanska, E. S (2017). Are fish outside their usual ranges early indicators of climate-driven range shifts? Global Change Biology 23, 2047–2057.

Fogarty, H. E., Cvitanovic, C., Hobday, A. J., & Pecl, G. T. (2019). Prepared for change? An assessment of the current state of knowledge to support climate adaptation for Australian fisheries. Reviews in Fish Biology and Fisheries, 1–18. https://doi.org/10.1007/s1116 0-019-09579-7

Fowler, A.M., Parkinson, K. & Booth, D.J (2018) New poleward observations of 30 tropical reef fishes in temperate southeastern Australia. Mar Biodiv 48, 2249–2254. https://doi.org/10.1007/s12526-017-0748-6

Graba-Landry, A., Champion, C., Haddy, J., Lyle, J., Mossop, D., Pearn, R., Pecl, G., Pethybridge, H., Wolfe, B., Tracey, S. (2022) Opportunities and impacts of range extending scalefish species: Understanding population dynamics, ecosystem impacts and management needs. Final report FRDC project 2018-070, Institute for Marine and Antarctic Studies, Hobart

García Molinos J, Hunt H, Green M, Champion C, Hartog J, Pecl GT (in review). Climate, currents and species traits contribute to early stages of marine species redistribution. Communications Biology

Gervais CR, Champion C, Pecl GT (2021) Species on the move around the Australian coastline: a continental scale review of climate-driven species redistribution in marine systems. Glob Change Biol 27: 3200−3217

Figueira WF, Biro P, Booth DJ, Valenzuela VC (2009) Performance of tropical fish recruiting to temperate habitats: role of ambient temperature and implications of climate change. Mar Ecol Prog Ser 384:231-239. https://doi.org/10.3354/meps08057

Hobday AJ, Pecl GT (2014) Identification of global marine hotspots: sentinels for change and vanguards for adaptation action. Review in Fish Biology and Fisheries, 24, 415–425.

Holbrook NJ, Scannell H, Sen Gupta A, Benthuysen J, Feng M, Oliver ECJ, Alexander LV, Burrows M, Donat MG, Hobday AJ, Moore PJ, Perkins-Kirkpatrick SE, Smale DA, Straub SC, Wernberg T (2019) A global assessment of marine heatwaves and their drivers Nature Communications, 10, 1–11.

IPCC (2019) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

IPCC, 2022: *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press.

Kelly, R., Fleming, A. & Pecl, G. Citizen science and social licence: Improving perceptions and connecting marine user groups. Ocean & Coastal Management 178, 104855 (2019).

Laufkötter C, Zscheischler J, Frölicher TL (2020) High-impact marine heatwaves attributable to human-induced global warming. Science, 369, 1621–1625.

Lawrence, J., B. Mackey, F. Chiew, M.J. Costello, K. Hennessy, N. Lansbury, U.B. Nidumolu, G. Pecl, L. Rickards, N. Tapper, A. Woodward, and A. Wreford, 2022: Australasia. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press.

Last, Peter R., et al. "Long-term shifts in abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices." *Global Ecology and Biogeography* 20.1 (2011): 58-72.

Ling SD (2008) Range expansion of a habitat-modifying species leads to loss of taxonomic diversity: a new and impoverished reef state. Oecologia, 156, 883-894.

Ling, S.D. and Keane, J.P. (2018) Resurvey of the longspined sea urchin (*Centrostephanus rodgersii*) and associated barren reef in Tasmania. Institute for Marine and Antarctic Studies Report. University of Tasmania, Hobart. 52 p

Martin VY, Christidis L, Pecl GT, (2016a). Public Interest in Marine Citizen Science: Is there Potential for Growth?, BioScience, Volume 66, Issue 8, Pages 683–692, https://doi.org/10.1093/biosci/biw070

Martin V, Smith L, Bowling A, Christidis L, Lloyd D, Pecl G. (2016b). Citizens as Scientists: What Influences Public Contributions to Marine Research? Science Communication, 38(4):495-522. doi:10.1177/1075547016656191

Martinez-Moreno J, Hogg AM, England MH, Constantinou NC, Kiss AE, Morrison AK (2021) Global changes in oceanic mesoscale currents over the satellite altimetry record. Nature Climate Change, 11, 397–403.

Marzloff MP, Melbourne-Thomas J, Hamon KG, Hoshino E, Jennings S, van Putten IE, Pecl GT (2016) Modelling marine community responses to climate-driven species redistribution to guide monitoring and adaptive ecosystem-based management. Global Change Biology, 22, 2462–2474.

Melbourne-Thomas J, Audzijonyte A, Brasier M, Cresswell KA, Fogarty HE, Haward M, Hobday A, Hunt HL, Ling SD, McCormack PC, Mustonen T, Mustonen K, Nye JA, Oellermann M, Trebilco R, van Putten I, Villanueva C, Watson RA, Pecl GT (2021) Poleward Bound: adapting to climate-driven species redistribution. Review in Fish Biology and Fisheries. 32, 231–251

Mourier, J., Buray, N., Schultz, J. K., Clua, E., & Planes, S. (2013). Genetic network and breeding patterns of a sicklefin lemon shark (*Negaprion acutidens*) population in the Society Islands, French Polynesia. PloS one, 8(8), e73899. https://doi.org/10.1371/journal.pone.0073899

Niella, Y., Butcher, P., Holmes, B., Barnett, A., & Harcourt, R. (2022). Forecasting intraspecific changes in distribution of a wide-ranging marine predator under climate change. Oecologia, 198(1), 111-124.

Nursey-Bray, M., Palmer, R., & Pecl, G. (2018) Spot, log, map: Assessing a marine virtual citizen science program against Reed's best practice for stakeholder participation in environmental management. Ocean and Coastal Management, 151, 1-9.

Oliver ECJ, Benthuysen J, Darmaraki S, Donat MG, Hobday AJ, Holbrook NJ, Schlegel RW, Sen Gupta A (2021) Marine Heatwaves. Annual Review of Marine Science, 13, 313–342.

Oliver ECJ, O'Kane TJ, Holbrook NJ (2015) Projected changes to Tasman Sea eddies in a future climate. Journal of Geophysical Research: Oceans, 120, 7150–7165.

Pecl, G.T. et al. (2019) Redmap Australia: challenges and successes with a large-scale citizen science-based approach to ecological monitoring and community engagement on climate change. Frontiers in Marine Science 6, 349.

Pecl, G. T., Araújo, M. B., Bell, J. D., et al. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science, 355(6332), eaai9214. https://doi.org/10.1126/scien ce.aai9214

Pecl, G.T., Ogier, E., Jennings, S. et al. (2019). Autonomous adaptation to climate-driven change in marine biodiversity in a global marine hotspot. Ambio 48, 1498–1515. https://doi.org/10.1007/s13280-019-01186-x

Poloczanska ES, Burrows MT, Brown CJ, García Molinos J, Halpern BS, Hoegh-Guldberg O, Kappel CV, Moore PJ, Richardson AJ, Schoeman DS and Sydeman WJ (2016) Responses of Marine Organisms to Climate Change across Oceans. Front. Mar. Sci. 3:62. doi:10.3389/fmars.2016.00062

Robinson LM, Gledhill DC, Moltschaniwskyj NA, Hobday AJ, Frusher S, N.Barrett, Stuart-Smith J, Pecl GT (2015) Rapid assessment of an ocean warming hotspot reveals "high" confidence in potential species' range extensions. Global Environmental Change, 31, 28–37.

Scheffers, B and G. Pecl (2019). Persecuting, protecting, or ignoring biodiversity under climate change. Nature Climate Change (9) 581-586

Smith JE, Keane J, Mundy C, Gardner C, Oellermann M (2022). Spiny lobsters prefer native prey over range-extending invasive urchins, ICES Journal of Marine Science, Volume 79, Issue 4, Pages 1353–1362, https://doi.org/10.1093/icesjms/fsac058

Stuart-Smith J, Pecl G, Pender A, Tracey S, Villanueva C, Smith-Vaniz WF (2018) Southernmost records of two Seriola species in an Australian ocean-warming hotspot. Marine Biodiversity, 48, 1579–1582.

Twiname S, Fitzgibbon QP, Hobday AJ, Carter CG, Oellermann M, Pecl GT (2022) Resident lobsters dominate food competition with range-shifting lobsters in an ocean warming hotspot. Mar Ecol Prog Ser 685:171-181. https://doi.org/10.3354/meps13984

Wolfe BW, Fitzgibbon QP, Semmens JM, Tracey SR, Pecl GT (2020) Physiological mechanisms linking cold acclimation and the poleward distribution limit of a range-extending marine fish. Conserv Physiol 8(1): coaa045; doi:10.1093/conphys/coaa045.

Appendix A

List of target species (200). "Out of Range" indicates whether the species had out-of-range observations (records from the citizen science databases beyond historical distribution limits)

Taxonomic group	Species	Standard Name	Out of Range?
Cnidarian	*Dofleinia armata*	Cockburn Sound Anemone	N
Cnidarian	*Pocillopora aliciae*	Branching Coral	Y
Crustacean	*Melicertus plebejus*	Eastern King Prawn	Y
Crustacean	*Ovalipes australiensis*	Common Sand Crab	N
Crustacean	*Panulirus ornatus*	Ornate Rocklobster	N
Crustacean	*Portunus armatus*	Blue Swimmer Crab	N
Crustacean	*Ranina ranina*	Spanner Crab	N
Crustacean	*Sagmariasus verreauxi*	Eastern Rock Lobster	Y
Crustacean	*Scylla serrata*	Giant Mud Crab	Y
Echinoderm	*Acanthaster planci*	Crown-of-thorns Seastar	N
Echinoderm	*Asterodiscides truncatus*	Firebrick Seastar	N
Echinoderm	*Centrostephanus rodgersii*	Longspine Sea Urchin	N
Echinoderm	*Centrostephanus tenuispinus*	Western Longspine Sea Urchin	N
Elasmobranch	*Carcharhinus albimarginatus*	Silvertip Shark	N
Elasmobranch	*Carcharhinus amblyrhynchos*	Grey Reef Shark	N
Elasmobranch	*Carcharhinus melanopterus*	Blacktip Reef Shark	N
Elasmobranch	*Carcharias taurus*	Greynurse Shark	N
Elasmobranch	*Galeocerdo cuvier*	Tiger Shark	Y
Elasmobranch	*Negaprion acutidens*	Lemon Shark	Y
Elasmobranch	*Neotrygon australiae*	Bluespotted Maskray	Y
Elasmobranch	*Pristiophorus delicatus*	Tropical Sawshark	N
Elasmobranch	*Pristis pristis*	Freshwater Sawfish	N
Elasmobranch	*Pristis zijsron*	Green Sawfish	N
Elasmobranch	*Squatina australis*	Australian Angel Shark	N
Elasmobranch	*Triaenodon obesus*	Whitetip Reef Shark	Y
Elasmobranch	*Trygonoptera imitata*	Eastern Shovelnose Stingaree	Y
Elasmobranch	*Trygonorrhina dumerilii*	Southern Fiddler Ray	N
Elasmobranch	*Trygonorrhina fasciata*	Eastern Fiddler Ray	N
Mammal	*Dugong dugon*	Dugong	N
Mammal	*Orcaella heinsohni*	Australian Snubfin Dolphin	N
Mammal	*Sousa sahulensis*	Australian Humpbacked Dolphin	N
Mammal	*Tursiops australis*	Burrunan Dolphin	Y
Mollusc	*Argonauta argo*	Greater Argonaut	Y
Mollusc	*Cypraea tigris*	Tiger Cowrie	N
Mollusc	*Octopus tetricus*	Gloomy Octopus	Y
Mollusc	*Pinna dolabrata*	Razor Clam	N
Mollusc	*Tridacna gigas*	Giant Clam	Y
Reptile	*Crocodylus porosus*	Saltwater Crocodile	N
Reptile	*Eretmochelys imbricata*	Hawksbill Turtle	N
Reptile	*Hydrophis platurus*	Yellow-bellied Seasnake	N
Teleost	*Abudefduf sexfasciatus*	Scissortail Sergeant	N
Teleost	*Abudefduf vaigiensis*	Indo-Pacific Sergeant	Y
Teleost	*Acanthistius ocellatus*	Eastern Wirrah	N
Teleost	*Acanthistius serratus*	Western Wirrah	N
Teleost	*Acanthocybium solandri*	Wahoo	Y
Teleost	*Acanthopagrus morrisoni*	Western Yellowfin Bream	N
Teleost	*Acanthurus lineatus*	Bluelined Surgeonfish	N
Teleost	*Achoerodus gouldii*	Western Blue Groper	Y
Teleost	*Achoerodus viridis*	Eastern Blue Groper	N
Teleost	*Albula argentea*	Pacific Bonefish	Y
Teleost	*Amphiprion percula*	Eastern Clown Anemonefish	N
Teleost	*Anoplocapros lenticularis*	Whitebarred Boxfish	Y
Teleost	*Antennarius striatus*	Striate Anglerfish	Y
Teleost	*Aphareus rutilans*	Rusty Jobfish	N

Teleost	*Aplodactylus lophodon*	Rock Cale	Y
Teleost	*Aprion virescens*	Green Jobfish	Y
Teleost	*Arotrolepis filicauda*	Threadfin Leatherjacket	Y
Teleost	*Atypichthys strigatus*	Mado	N
Teleost	*Auxis thazard*	Frigate Mackerel	Y
Teleost	*Bodianus axillaris*	Coral Pigfish	N
Teleost	*Bodianus frenchii*	Foxfish	N
Teleost	*Carangoides chrysophrys*	Longnose Trevally	Y
Teleost	*Carangoides fulvoguttatus*	Goldspotted Trevally	N
Teleost	*Carangoides plagiotaenia*	Barcheek Trevally	N
Teleost	*Caranx ignobilis*	Giant Trevally	Y
Teleost	*Centropyge tibicen*	Keyhole Angelfish	Y
Teleost	*Chaetodon assarius*	Western Butterflyfish	N
Teleost	*Chaetodon auriga*	Threadfin Butterflyfish	Y
Teleost	*Chaetodon citrinellus*	Citron Butterflyfish	N
Teleost	*Chaetodon kleinii*	Klein's Butterflyfish	N
Teleost	*Chaetodon melannotus*	Blackback Butterflyfish	N
Teleost	*Chaetodon meyeri*	Meyer's Butterflyfish	N
Teleost	*Chaetodon rafflesii*	Lattice Butterflyfish	N
Teleost	*Chaetodon ulietensis*	Doublesaddle Butterflyfish	N
Teleost	*Chaetodontoplus ballinae*	Ballina Angelfish	N
Teleost	*Chaetodontoplus meredithi*	Queensland Yellowtail Angelfish	N
Teleost	*Chaetodontoplus personifer*	Yellowtail Angelfish	Y
Teleost	*Cheilodactylus fuscus*	Red Morwong	N
Teleost	*Chlorurus japanensis*	Redtail Parrotfish	N
Teleost	*Choerodon rubescens*	Baldchin Groper	N
Teleost	*Choerodon schoenleinii*	Blackspot Tuskfish	N
Teleost	*Chromis hypsilepis*	Onespot Puller	Y
Teleost	*Chromis nitida*	Yellowback Puller	N
Teleost	*Chrysophrys auratus*	Snapper	N
Teleost	*Cleidopus gloriamaris*	Australian Pineapplefish	N
Teleost	*Coris picta*	Comb Wrasse	N
Teleost	*Coryphaena hippurus*	Mahi Mahi	Y
Teleost	*Dactylophora nigricans*	Dusky Morwong	Y
Teleost	*Dactyloptena orientalis*	Purple Flying Gurnard	N
Teleost	*Dascyllus reticulatus*	Headband Humbug	Y
Teleost	*Diploprion bifasciatum*	Barred Soapfish	Y
Teleost	*Eleutheronema tetradactylum*	Blue Threadfin	N
Teleost	*Elops hawaiensis*	Hawaiian Giant Herring	N
Teleost	*Enoplosus armatus*	Old Wife	Y
Teleost	*Epinephelus coioides*	Goldspotted Rockcod	N
Teleost	*Epinephelus lanceolatus*	Queensland Groper	N
Teleost	*Epinephelus multinotatus*	Rankin Cod	Y
Teleost	*Epinephelus tukula*	Potato Rockcod	Y
Teleost	*Eubalichthys mosaicus*	Mosaic Leatherjacket	N
Teleost	*Eupetrichthys angustipes*	Snakeskin Wrasse	N
Teleost	*Girella elevata*	Rock Blackfish	Y
Teleost	*Girella tricuspidata*	Luderick	Y
Teleost	*Girella zebra*	Zebrafish	N
Teleost	*Glaucosoma scapulare*	Pearl Perch	Y
Teleost	*Grammatorcynus bicarinatus*	Shark Mackerel	Y
Teleost	*Gymnosarda unicolor*	Dogtooth Tuna	Y
Teleost	*Gymnothorax eurostus*	Stout Moray	Y
Teleost	*Gymnothorax prasinus*	Green Moray	N
Teleost	*Heterodontus galeatus*	Crested Hornshark	Y
Teleost	*Heteroscarus acroptilus*	Rainbow Cale	N
Teleost	*Hippocampus histrix*	Spiny Seahorse	Y
Teleost	*Hypoplectrodes maccullochi*	Halfbanded Seaperch	N
Teleost	*Hyporthodus ergastularius*	Banded Rockcod	Y
Teleost	*Istiompax indica*	Black Marlin	N
Teleost	*Kajikia audax*	Striped Marlin	N
Teleost	*Kyphosus sydneyanus*	Silver Drummer	N
Teleost	*Lactoria fornasini*	Thornback Cowfish	N
Teleost	*Lates calcarifer*	Barramundi	Y

Teleost	*Latropiscis purpurissatus*	Sergeant Baker	Y
Teleost	*Lethrinus miniatus*	Redthroat Emperor	Y
Teleost	*Lethrinus nebulosus*	Spangled Emperor	Y
Teleost	*Lethrinus ornatus*	Ornate Emperor	N
Teleost	*Lobotes surinamensis*	Tripletail	N
Teleost	*Lutjanus argentimaculatus*	Mangrove Jack	Y
Teleost	*Lutjanus erythropterus*	Crimson Snapper	N
Teleost	*Lutjanus johnii*	Golden Snapper	Y
Teleost	*Lutjanus quinquelineatus*	Fiveline Snapper	Y
Teleost	*Lutjanus rivulatus*	Maori Snapper	N
Teleost	*Lutjanus russellii*	Moses' Snapper	N
Teleost	*Lutjanus sebae*	Red Emperor	Y
Teleost	*Macolor macularis*	Midnight Snapper	N
Teleost	*Macquaria colonorum*	Estuary Perch	N
Teleost	*Macroramphosus gracilis*aaa	Little Bellowsfish	N
Teleost	*Makaira nigricans*	Blue Marlin	Y
Teleost	*Monotaxis grandoculis*	Bigeye Seabream	N
Teleost	*Naso unicornis*	Bluespine Unicornfish	Y
Teleost	*Neatypus obliquus*	Footballer Sweep	N
Teleost	*Nemadactylus douglasii*	Grey Morwong	Y
Teleost	*Nemadactylus valenciennesi*	Blue Morwong	N
Teleost	*Neopataecus waterhousii*	Whiskered Prowfish	N
Teleost	*Notolabrus gymnogenis*	Crimsonband Wrasse	N
Teleost	*Olisthops cyanomelas*	Herring Cale	N
Teleost	*Ophthalmolepis lineolatus*	Southern Maori Wrasse	N
Teleost	*Othos dentex*	Harlequin Fish	N
Teleost	*Parachaetodon ocellatus*	Ocellate Butterflyfish	Y
Teleost	*Parapercis ramsayi*	Spotted Grubfish	Y
Teleost	*Parazanclistius hutchinsi*	Short Boarfish	N
Teleost	*Paristiopterus labiosus*	Giant Boarfish	N
Teleost	*Parma microlepis*	White-ear	Y
Teleost	*Parupeneus ciliatus*	Diamondscale Goatfish	N
Teleost	*Parupeneus cyclostomus*	Goldsaddle Goatfish	N
Teleost	*Parupeneus pleurostigma*	Sidespot Goatfish	N
Teleost	*Parupeneus spilurus*	Blacksaddle Goatfish	Y
Teleost	*Pentapodus paradiseus*	Paradise Threadfin Bream	Y
Teleost	*Pervagor janthinosoma*	Gillblotch Leatherjacket	N
Teleost	*Platax orbicularis*	Round Batfish	N
Teleost	*Platax teira*	Roundface Batfish	N
Teleost	*Platycephalus endrachtensis*	Northern Sand Flathead	N
Teleost	*Plectorhinchus gibbosus*	Brown Sweetlips	N
Teleost	*Plectorhinchus lineatus*	Oblique-banded Sweetlips	Y
Teleost	*Plectroglyphidodon dickii*	Dick's Damsel	Y
Teleost	*Plectroglyphidodon fasciolatus*	Pacific Gregory	N
Teleost	*Plectropomus laevis*	Bluespotted Coral Trout	Y
Teleost	*Plectropomus leopardus*	Common Coral Trout	Y
Teleost	*Pomacanthus xanthometopon*	Blueface Angelfish	N
Teleost	*Pomacentrus bankanensis*	Speckled Damsel	N
Teleost	*Premnas biaculeatus*	Spine-cheek Clownfish	Y
Teleost	*Prionurus microlepidotus*	Australian Sawtail	N
Teleost	*Pristipomoides multidens*	Goldband Snapper	N
Teleost	*Pristotis obtusirostris*	Gulf Damsel	N
Teleost	*Pseudogoniistius nigripes*	Magpie Perch	N
Teleost	*Pseudolabrus biserialis*	Redband Wrasse	Y
Teleost	*Pterois volitans*	Common Lionfish	Y
Teleost	*Rachycentron canadum*	Cobia	N
Teleost	*Ranzania laevis*	Slender Sunfish	N
Teleost	*Scarus ghobban*	Bluebarred Parrotfish	Y
Teleost	*Scomberomorus commerson*	Spanish Mackerel	N
Teleost	*Scomberomorus semifasciatus*	Grey Mackerel	N
Teleost	*Scorpis georgiana*	Banded Sweep	Y
Teleost	*Seriola lalandi*	Yellowtail Kingfish	Y
Teleost	*Siganus fuscescens*	Black Rabbitfish	Y
Teleost	*Sillaginodes punctatus*	King George Whiting	N

Teleost	*Sillago schomburgkii*	Yellowfin Whiting	N
Teleost	*Stegastes gascoynei*	Coral Sea Gregory	N
Teleost	*Stethojulis bandanensis*	Redspot Wrasse	Y
Teleost	*Stethojulis interrupta*	Brokenline Wrasse	N
Teleost	*Stethojulis trilineata*	Three-Ribbon Wrasse	N
Teleost	*Sufflamen chrysopterum*	Eye-Stripe Triggerfish	N
Teleost	*Thalassoma jansenii*	Jansen's Wrasse	N
Teleost	*Thalassoma lunare*	Moon Wrasse	N
Teleost	*Thalassoma lutescens*	Green Moon Wrasse	Y
Teleost	*Thunnus albacares*	Yellowfin Tuna	N
Teleost	*Torquigener pallimaculatus*	Rusty-Spotted Toadfish	N
Teleost	*Trachichthys australis*	Southern Roughy	N
Teleost	*Trachinotus botla*	Common Dart	Y
Teleost	*Variola louti*	Yellowedge Coronation Trout	N
Teleost	*Wattsia mossambica*	Mozambique Seabream	Y
Teleost	*Xiphasia setifer*	Hairtail Blenny	Y
Teleost	*Zanclus cornutus*	Moorish Idol	Y
Teleost	*Zebrasoma scopas*	Brown Tang	N

Appendix B

Details of range extension assessment results. Detectability criteria are displayed for potential extensions where detectability influences strength of evidence estimates i.e., when not observed in multiple years, or during winter (non-mobile species only). Species primarily observed through fishing captures (for which detectability is only influenced by abundance) are noted with an "F" in the conspicuousness column. For species not primarily observed through fishing, because detectability was "High" only if both conspicuousness and abundance are High, conspicuousness (Low ≥ 2 more of the following: < 30 cm length, camouflage, hiding behaviour; otherwise High) was first assessed, and abundance (High = common, Low: patchy or rare) was assessed for low-conspicuousness species.

Migratory Species (evidence assessment not influenced by presence of winter observations):

		Observed in:		Detectability criteria			
Species	State	Winter	Multiple Years	Conspicuous -ness	Abundance	Detect-ability	Strength of evidence
Gymnosarda unicolor	NSW	Yes	Yes	-	-		High
Argonauta argo	TAS	No	Yes	-	-		High
Arotrolepis filicauda	TAS	No	Yes	-	-		High
Coryphaena hippurus	TAS	No	Yes	-	-		High
Galeocerdo cuvier	TAS	No	Yes	-	-		High
Melicertus plebejus	TAS	No	Yes	-	-		High
Seriola lalandi	TAS	No	Yes	-	-		High
Grammatorcynus bicarinatus	WA	No	Yes	-	-		High
Lethrinus nebulosus[a]	NSW	No	Yes	-	-		High
Acanthocybium solandri	SA	No	No	F	High	High	Low
Trachinotus botla	WA	No	No	F	High	High	Low
Makaira nigricans	SA	No	No	High[b]	-	High	Low
Auxis thazard	TAS	No	No	F	Low	Low	Med
Negaprion acutidens[c]	NSW	No	No	High	-		Low

a Evidence of spawning-related migrations of 130 km (Babcock et al. 2017)
b Observations were beach wash-ups.
c Evidence of spawning-related migrations over 10s of km (Mourier et al. 2013)

Non-migratory species with 'High' estimated strength of evidence (detected in winter and in multiple years, estimate not influenced by detectability).

		Observed in:		
Species	State	Winter	Multiple Years	Strength of Evidence
Abudefduf vaigiensis	WA	Yes	Yes	High
Anoplocapros lenticularis	VIC	Yes	Yes	High
Aprion virescens	WA	Yes	Yes	High
Dactylophora nigricans	TAS	Yes	Yes	High
Dascyllus reticulatus	NSW	Yes	Yes	High
Diploprion bifasciatum	WA	Yes	Yes	High
Girella elevata	TAS	Yes	Yes	High

Gymnothorax eurostus	NSW	Yes	Yes	High
Heterodontus galeatus	NSW	Yes	Yes	High
Hyporthodus ergastularius	NSW	Yes	Yes	High
Lethrinus miniatus	WA	Yes	Yes	High
Lutjanus sebae	WA	Yes	Yes	High
Naso unicornis	NSW	Yes	Yes	High
Nemadactylus douglasii	TAS	Yes	Yes	High
Pentapodus paradiseus	NSW	Yes	Yes	High
Pocillopora aliciae	NSW	Yes	Yes	High
Pseudolabrus biserialis	SA	Yes	Yes	High
Pterois volitans	WA	Yes	Yes	High
Sagmariasus verreauxi	TAS	Yes	Yes	High
Scarus ghobban	NSW	Yes	Yes	High
Siganus fuscescens	WA	Yes	Yes	High
Thalassoma lutescens	NSW	Yes	Yes	High
Zanclus cornutus	WA	Yes	Yes	High

Non-migratory species with 'Low' or 'Medium' strength of evidence (not detected in multiple years and/or not detected in winter).

		Observed in:		Detectability criteria			
Species	State	Winter	Multiple Years	Conspicuous-ness	Abundance	Detect-ability	Strength of evidence
Hippocampus histrix	NSW	No	Yes	Low	Low	Low	Med
Antennarius striatus	NSW/VIC	No	Yes	Low	Low	Low	Med
Centropyge tibicen	WA	No	Yes	Low	Low	Low	Med
Scylla serrata	WA	No	Yes	Low	Low	Low	Med
Octopus tetricus	TAS	No	No	Low	Low	Low	Med
Parapercis ramsayi	VIC	No	No	Low	Low	Low	Med
Epinephelus multinotatus	WA	No	Yes	F	High	High	Low
Xiphasia setifer[c]	NSW/TAS	No	No	High	-	High	Low
Girella tricuspidata	TAS	No	Yes	High	-	High	Low
Diploprion bifasciatum	NSW	Yes	No	High	-	High	Low
Triaenodon obesus	NSW	Yes	No	High	-	High	Low
Albula argentea	WA	Yes	No	F	High	High	Low
Glaucosoma scapulare	NSW	No	Yes	High	-	High	Low
Plectropomus leopardus	NSW	No	Yes	High	-	High	Low
Zebrasoma scopas	NSW	No	Yes	High	-	High	Low
Caranx ignobilis	NSW	No	No	High	-	High	Low
Lutjanus quinquelineatus	NSW	No	No	High	-	High	Low
Plectroglyphidodon dickii	NSW	No	No	Low	High	High	Low
Epinephelus tukula	QLD	No	Yes	High	-	High	Low
Chromis hypsilepis	TAS	No	Yes	High	-	High	Low
Enoplosus armatus	TAS	No	Yes	High	-	High	Low
Trygonorrhina dumerilii	TAS	No	Yes	High	-	High	Low

Chromis hypsilepis	VIC	No	Yes	High	-	High	Low
Variola louti	WA	No	Yes	High	-	High	Low
Plectorhinchus lineatus	QLD	No	No	High	-	High	Low
Premnas biaculeatus	QLD	No	No	High	-	High	Low
Lutjanus johnii	QLD/NSW	No	No	High	-	High	Low
Sagmariasus verreauxi	SA	No	No	High	-	High	Low
Aplodactylus lophodon	TAS	No	No	High	-	High	Low
Latropiscis purpurissatus	TAS	No	No	High	-	High	Low
Trygonoptera imitata	TAS	No	No	High	-	High	Low
Aplodactylus lophodon	VIC	No	No	High	-	High	Low
Parma microlepis	VIC	No	No	High	-	High	Low
Plectropomus laevis	VIC	No	No	High	-	High	Low
Scorpis georgiana	VIC	No	No	High	-	High	Low
Carangoides chrysophrys	WA	No	No	High	-	High	Low
Chaetodon auriga	WA	No	No	High	-	High	Low
Chaetodontoplus personifer	WA	No	No	High	-	High	Low
Gymnothorax eurostus	WA	No	No	High	-	High	Low
Lutjanus argentimaculatus	WA	No	No	High	-	High	Low
Neotrygon australiae	WA	No	No	High	-	High	Low
Parachaetodon ocellatus	WA	No	No	High	-	High	Low
Parupeneus spilurus	WA	No	No	High	-	High	Low
Stethojulis bandanensis	WA	No	No	High	-	High	Low
Lates calcarifer	QLD	No	Yes	F	High	High	Low

A

CONTACT

Name: Gretta Pecl & Barrett Wolfe

Email: Gretta.Pecl@utas.edu.au & Barrett.Wolfe@utas.edu.au

Web: https://marinesocioecology.org/

https://www.imas.utas.edu.au/

https://www.redmap.org.au/

This project is supported with funding
from the Australian Government under the
National Environmental Science Program.