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Continental-Scale Assessment of Climate-Driven Marine Species Range Extensions Using a Decade of Citizen Science Data

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ABSTRACT

Aim: Climate-driven extensions of species distributions have serious consequences for human wellbeing and ecosystems. The recent growth of citizen science data collection represents an underutilised resource for the early detection of marine species range extensions (i.e., expansion of species' distributions at the poleward edge) that can enable proactive conservation and management. Here, we present a framework for the systematic assessment of evidence for marine species range extensions along a continent's coastlines from observations collected by different citizen science programmes.

Location: Australia's coastal oceans.

Methods: Observations of 200 marine species on a pre-registered target list from around Australia during 2013–2022 were sourced from the citizen science databases Redmap Australia, iNaturalist, and Reef Life Survey. We established historical (circa 2012) poleward distribution limits for populations of target species and identified out-of-range (poleward of distribution limit) observations, which underwent expert validation. We assessed the likelihood that each species underwent range extension using a decision tree informed by citizen science observations and species traits.

Results: In total, 73 species (39%) were observed out-of-range, comprising 76 range extensions along different coastlines. Twenty-five range extensions were assessed as high confidence, five with medium confidence, and 46 with low confidence. Range extensions were concentrated in Australia's southwest (Western Australia) and southeast (New South Wales and Tasmania), which are influenced by warm boundary currents and considered ocean warming hotspots. The mean extent of range extensions was 318 km (max. 1250 km).

Main Conclusions: As most (91%) range extensions identified were not previously described in the scientific literature from other data, we demonstrate that opportunistic citizen science monitoring can provide early detection of marine species range extensions at the continental scale. Given the varied consequences of range-extending species for recipient ecosystems, effectively harnessing citizen science would critically enhance the capacity for needed targeted research and anticipatory management efforts.

1 | Introduction

Since the 19th century, the ocean has absorbed 91% of added heat to the Earth's system, resulting in an average ocean surface temperature increase of 1.10°C (IPCC 2021; Rohde 2024). Changes in atmospheric conditions have driven major shifts in ocean currents, eddies, and upwellings (Martinez-Moreno et al. 2021), and marine heatwaves have increased in frequency, duration, and intensity (Laufkötter et al. 2020). In response, marine species are redistributing, with geographical shifts of their equatorward (warm) and/or poleward (cool) distribution limits. These range contractions and range expansions, respectively, are largely toward the poles or to greater water depths, consistent with expectations given geographical shifts in the species' suitable climatic conditions (Poloczanska et al. 2013; IPCC 2022). Range extensions and contractions generally occur faster in regions that are warming most rapidly (Pinsky et al. 2013; Poloczanska et al. 2016). The climate-driven redistribution of species can have serious economic and social ramifications, including for conservation, commercial, recreational, and Indigenous fisheries, food security, livelihoods, human health, and culture (Pecl et al. 2017; Bonebrake et al. 2018).

Two ocean warming hotspots occur in the Australian region, where increases in ocean temperature are among the top 10% of most rapidly warming ocean regions globally (Hobday and Pecl 2014; Li et al. 2023). The southeast coast of Australia is a hotspot warming at a rate around four times the global average, primarily due to the climate-driven strengthening of the warm, poleward-flowing East Australian Current (herein 'EAC', Oliver et al. 2015). This region has experienced multiple marine heatwaves since 2015 (Holbrook et al. 2019), with peak intensities of 1.5°C–3°C above long-term averages (Oliver et al. 2021). Likewise, waters around southwest Australia are warming at nearly three times the global average (Hobday and Pecl 2014) and have also experienced strong marine heatwaves in recent years (Pearce and Feng 2013; Holbrook et al. 2019).

Associated with rising ocean temperatures around Australia, many changes to the geographic distributions of species have been reported, with both range contractions at the warmer, equatorial range edges and range extensions at cooler, poleward range edges (e.g., Champion et al. 2021; Davis et al. 2021a; Shalders et al. 2018). Poleward range extensions represent species arriving and persisting in new areas once local conditions (e.g., water temperatures) become suitable (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) occurring in a poleward direction and therefore aligned with expectations under warming trends. This study also highlighted that the number of documented marine species undergoing range shifts around the Australian continent was almost certainly a considerable underestimate, due to limited standardised monitoring and spatial and taxonomic bias in monitoring that has occurred (Gervais et al. 2021).

While both range contractions and range extensions are of conservation concern, marine range extensions are outpacing range contractions by more than four times on average (Poloczanska et al. 2013) and in subtropical and temperate marine ecosystems (i.e., most of Australia's coastlines), are projected to be a primary driver of ongoing biodiversity change (García Molinos et al. 2022; Pecl et al. 2017). Ecological consequences of range extenders vary greatly, but some have had substantial consequences for recipient marine ecosystems around Australia (e.g., Ling 2008). The capacity to identify novel, range-extending species in recipient ecosystems is critical because it enables the development of anticipatory marine conservation and resource management strategies (Melbourne-Thomas et al. 2021; Scheffers and Pecl 2019). Early detection of range-extending species can provide advanced warning of incipient consequences, allowing proactive research and implementation of adaptation measures (Marzloff et al. 2016; Twiname et al. 2022; Smith et al. 2022; Ling and Keane 2024).

While changes in species distributions are ideally assessed through targeted, repeated surveys (Booth et al. 2011; Ling and Keane 2018), insights can be provided through opportunistically collected citizen science data. These data are better suited to providing evidence of range extensions than range contractions, as single observations can provide evidence for the occurrence of a novel species in an area, however establishing the loss of a species in an area indicative of a contraction is not as straightforward because of the problem of induction (i.e., it is difficult to 'prove a negative'). Opportunistic citizen science data are particularly valuable in the early stages of species range extensions when occurrences in new areas are extraordinary and/or intermittent, as the cost-effectiveness of targeted traditional scientific surveys is generally prohibitive.

Citizen science programs can provide reliable evidence for marine species range extensions via repeated observations of species beyond their historical distributions (Robinson et al. 2015;

Stuart-Smith et al. 2018; Pecl, Stuart-Smith, et al. 2019; Middleton et al. 2021). By engaging fishers, divers, and other marine users to report these observations, citizen science programs can also help engage marine users on issues related to climate change using their own data (Nursey-Bray et al. 2018; Kelly et al. 2019). Local monitoring activities are an important component of environmental stewardship, which can further engage local communities, improve ecological and social values, and ultimately result in measurable improvements in ecosystem health through "virtuous cycles" as the desirable outcomes of participation reinforce further participation (Turnbull et al. 2020; Turnbull et al. 2021). However, information being logged and recorded via citizen science programs needs to be collated, validated, and systematically assessed to evaluate which species are shifting. In isolation, single observations of species beyond their historical range limits may not definitively indicate an ongoing range extension (Fogarty et al. 2017). It is essential to analyse patterns over time, considering both species' historical range limits and the weight of evidence that species are now occurring beyond these limits. Notably, the past decade has witnessed substantial growth in the collection of marine citizen science data (e.g., Pecl, Stuart-Smith, et al. 2019; Edgar et al. 2020; DiBattista et al. 2021), enabling the comprehensive examination of occurrence patterns over time.

This study aimed to identify marine species range extensions by analysing a decade of opportunistically collected citizen science data around the Australian continent. We provide a qualitative decision tree framework that we used to systematically evaluate evidence for species range extensions, incorporating historical species distributions, species traits, and recent citizen science records from three databases. Assessments of potential range extensions for marine species around Australia during the decade spanning 2013–2022 produced through this framework are presented. Additionally, we explore the degree to which citizen science can complement formal scientific monitoring to provide early indications of species' range extensions. Finally, we provide examples of 'report cards' for repatriating information on species redistributions to citizen scientists and other stakeholders.

2 | Methods

To assess the available evidence for Australian marine species range extensions, we undertook a four-step process. First, we collated observations from three marine citizen science programs operating around Australia. Second, we assessed and verified available information on species distribution, including expert knowledge. Third, we determined historical (herein defined as before 2013) poleward range limits for relevant species using the method developed and applied by Pecl, Stuart-Smith, et al. (2019) and García Molinos et al. (2022). Finally, we assessed the weight of evidence that a range extension has occurred since 2012 with an adaptation of the decision tree framework developed by Robinson et al. (2015).

2.1 | Overview of Species Occurrence Data

We incorporated occurrence data from three citizen science sources: a specialised range extension-focused project (Redmap Australia; https://www.redmap.org.au) and two generalist biodiversity monitoring programs, iNaturalist (in particular, the Australasian Fishes Project; https://www.inaturalist.org/projects/australasian-fishes) and Reef Life Survey (https://reeflifesurvey.com).

2.1.1 | Redmap Australia

The Range Extension Database and Mapping Project (henceforth 'Redmap'), provides the public with an online platform to report sightings of marine species not typically seen in localised marine environments. Sightings are supported with photographic evidence submitted to the website or via the associated smartphone application. Regional 'target' species lists identify possible range-extending species for defined regions, or users can submit observations for any marine species they consider unusual in an area. Submitted observations are reviewed by a relevant taxon expert to verify the species identity and associated metadata (e.g., geolocation and approximate body size). The Redmap database contains citizen science observations collected from Tasmania since 2009 and from 2012 onward in New South Wales, South Australia, Western Australia, Victoria and Queensland. The Redmap project is described in full by Pecl, Stuart-Smith, et al. (2019). We exported 3576 validated observations from the Redmap database for assessment on 20 February 2022.

2.1.2 | iNaturalist

Like Redmap, iNaturalist collects observations of organisms with associated photographs submitted by the public since its launch in 2008, but with broader scope: any biological observations worldwide are accepted. Another key difference between iNaturalist and Redmap is that taxonomic identification of observations logged with iNaturalist occurs through crowdsourcing. This process results in species observations that are considered 'verifiable' if associated with a date, geolocation, media (e.g., photograph), and are wild (i.e., not captive/captively bred). All registered iNaturalist users can submit identification suggestions for an observation, and when at least two-thirds of identifiers agree on a taxon identification for a verifiable observation, the observation receives a 'research grade' rating. While many taxon experts are iNaturalist users, not all 'research grade' iNaturalist observations will have undergone expert verification. Accordingly, iNaturalist records underwent an additional verification screening for this process (see *Data quality verification*). Within the broader iNaturalist platform are discrete 'projects' that curate observations within specific locations and taxonomic criteria. For example, the 'Australasian Fishes Project', initiated in October 2016. The Australasian Fishes Project facilitates collection of observations of fishes from Australia and New Zealand, and data collected by this project have been used to map species distributions for conservation and biodiversity monitoring (DiBattista et al. 2021, 2022; Middleton et al. 2023). Data from the Australasian Fishes project within the area bounded by 9°–45°S and 110°–160°E were extracted through the iNaturalist website (https://www.inaturalist.org/observations/export) on 20 February 2022, which included approximately 136,000 observations. For non-fish species on the assessment list (i.e., species not within the scope of the Australasian Fishes project), relevant data were extracted from iNaturalist using targeted queries informed by species' scientific names.

2.1.3 | Reef Life Survey

Reef Life Survey (henceforth 'RLS') records species occurrences during SCUBA dives using a standardised method applied by professional scientists and citizen scientists that have undergone rigorous training (Edgar and Stuart-Smith 2014). As such, species are identified by trained divers in situ, so photographic evidence is not always collected and associated with RLS data. However, the RLS data importing process has a rigorous quality control stage in which unusual (e.g., out-of-range) observations are flagged for verification. These flagged observations are then investigated, and often, photographic evidence is sought from the submitting diver before the data are accepted into the RLS database. However, photographs are not systematically stored with publicly available RLS occurrence data.

RLS data were obtained from the Australian Ocean Data Network (https://portal.aodn.org.au) on 25 January 2022. The RLS global reef fish abundance and biomass, cryptobenthic fish abundance, off-transect species observations, and mobile macroinvertebrate abundance datasets were extracted within the area bounded by 9°–45°S and 110°–160°E. Non-RLS data captured within this extraction (i.e., "program" = ATRC or Parks Vic) were removed. This resulted in 629,000 observations (excluding duplicate species within a single survey dive) representing 3282 taxa.

2.2 | Species List

Redmap maintains a list of target species thought to be likely to undergo geographic redistributions related to ocean warming (https://www.redmap.org.au/species). As part of the listing process, the historical distributions of target species were established from scientific literature and expert advice from taxonomic experts (see Pecl, Stuart-Smith, et al. 2019). Most target species ($n = 159$) were listed on the Redmap website prior to 2013. An additional 17 species have been added since, for climate-impact monitoring in Queensland (listed in 2017) and others where evidence suggests range extensions may be underway (e.g., the coral *Pocillopora aliciae*; Booth and Sear 2018). This Redmap target species list (176 species) served as the basis for the current assessment. We also included 20 species that recently had historical distribution limits established (via the same process as Redmap target species) as part of a recent study that utilised Redmap data (García Molinos et al. 2022). Finally, four other species that are pending Redmap listing due to evidence of potential range shifting were also included (Wahoo, *Acanthocybium solandri*, Greater Argonaut, *Argonauta argo*, Eastern Shovelnose Stingaree, *Trygonoptera imitata*, and Redband Wrasse, *Pseudolabrus biserialis*). In total, the target species list for this study contained 200 species (Table S1), including two cnidarians, seven crustaceans, 16 elasmobranchs, four marine mammals, five molluscs, three reptiles, and 159 teleost fishes.

2.3 | Assessment Methodology

To assess the confidence associated with species range extension detected using citizen science data, we adapted the qualitative decision tree framework developed for the rapid assessment of potential range extensions of Tasmanian marine species by Robinson et al. (2015). Amendments were made during a series of workshops held between October and December 2021, attended by species experts from academic institutions, natural resource managers from Australian state governments, fisheries stakeholders, and representatives from each of the citizen science programs included in this assessment. Our alterations reflected new knowledge from the recent scientific literature about range extensions, facilitated the application of the framework across the entire Australian marine domain, and provided a structured framework for incorporating data from different citizen science programs. Each amendment to the method developed by Robinson et al. (2015) is presented in Table S1. The initial method developed by Robinson et al. (2015) has been adapted in other contexts to support the detection of alien species arrivals and range extensions across multiple life stages (Middleton et al. 2021).

Briefly, our revised qualitative decision tree framework (Figure 1) produces estimates of overall confidence in species range extensions by combining classifications of confidence in species' historical poleward distribution limits at a given time point (herein, 2012) and evidence of species occurrence poleward of historical distribution limits from validated citizen science observations. This 'strength of evidence' assessment accounts for species traits that relate to the probability of detection or expected species seasonal dynamics (e.g., mobility). For example, in cases where 'highly mobile' species have not been detected in multiple years, 'detectability' determines the final strength of evidence estimate classification (Figure 1). Highly mobile species include highly migratory and pelagic species, and species for which there is published evidence of regional-scale migration (~100 km+). Winter was defined as a four-month period encompassing the three consecutive months with the lowest annual mean water temperatures and the following month in the region a sighting is observed, as observations made in this period provide evidence of potential overwintering (see Table S1 and Figure S1; Figueira et al. 2009). Detectability was determined as follows: If a species' abundance or conspicuousness is 'High', then detectability is 'High', otherwise detectability is 'Low'. Species encountered almost exclusively by fishers (e.g., occurring beyond recreational SCUBA depths or in turbid habitats) are an exception where detectability was based solely on abundance, since conspicuousness does not influence catchability. Species abundance was 'Low' if patchy or rare in their endemic range, or 'High' if common. Conspicuousness was 'Low' if two or more of the following applied: total body length is less than 30 cm, the species is camouflaged, or it exhibits hiding/cryptic behaviour. Qualitative abundance data were retrieved from Reef Life Survey species pages (https://reeflifesurvey.com/species/search.php) or sourced from expert opinion and species size data were extracted from FishBase (https://www.fishbase.se). See Table S5 for details of the detectability assessment.

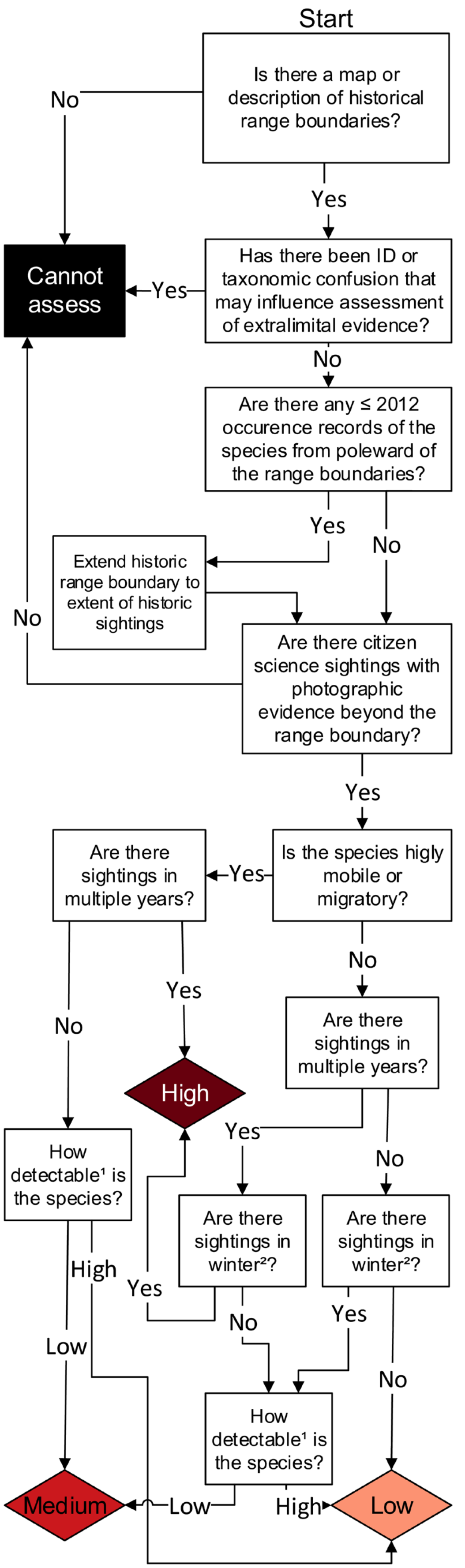

FIGURE 1 | Overview of the qualitative decision tree framework used to assess level of confidence (coloured diamonds labelled High, Medium, and Low) in potential marine species range extensions identified using citizen science observations since 2012. 'Highly mobile' species are species known to migrate at regional (~100 km) scale. (1) Detectability is based on conspicuousness and abundance scores, or abundance only for species solely encountered by fishers (see Methods subsection *Assessment methodology*). (2) 'Winter' in this framework represents a 4-month period spanning the 3 months with the minimum mean sea surface temperature and the following month in species occurrence regions (see Figure S1) to account for evidence of potential for species overwintering.

2.4 | Data Quality Verification

Our target species list was cross-checked against data from "Eye on the Reef Sightings Network" which is a Great Barrier Reef-specific citizen science monitoring project that has collected species occurrence data since 2007 (GBRMPA 2025). However, no records of target species occurred in this dataset beyond expected historical distribution limits. Duplicate records (e.g., the same individual species observation reported to more than one of the citizen science programs) were identified and removed by filtering observations of the same species at the same geographical coordinates (decimal degrees rounded to three decimal places) on the same date. Spurious records (e.g., those associated with dubious location or other metadata) from iNaturalist, and Reef Life Survey were screened by examining maps of each species' occurrence data in consultation with representatives from the leadership of each program.

To ensure that all iNaturalist species observations included in our assessment had undergone expert verification, we undertook a three-step process. Firstly, we queried the iNaturalist API (https://api.inaturalist.org/v1/) for the identifiers of out-of-range target species observations, and the user names of identifiers (286 total) that had made at least one putatively out-of-range target species identification were extracted. Secondly, a list of iNaturalist users known to be experts of identified taxa (professional biologists, museum curators, taxonomists, etc.) was developed, with advice from the Australasian Fishes project curator. Finally, the putatively out-of-range observations that had not been identified previously by an iNaturalist user on the expert list were flagged for review by a relevant expert either within the iNaturalist platform or externally. The iNaturalist observations for which species identifications could be confirmed by a taxon expert were then included in the assessment.

The assessment was conducted with a standard of photographic evidence at the maximum extent of species range extensions that could be independently verified, as is available with Redmap and iNaturalist sightings. While RLS routinely investigates unusual species sightings when survey data are submitted by trained divers, including review of available photographic evidence, photographs are not stored with the publicly available occurrence data. As such, out-of-range RLS data were included in the assessment for species which were recorded further poleward in the Redmap and iNaturalist databases to provide corroborative information (e.g., evidence of species overwintering and multi-year persistence) that influenced the confidence assessment (see *Assessment methodology*).

2.5 | Assessment of Species Historical Distributions

Historical geographic distribution limits of all Redmap target-listed species established at the inception of this project in 2009 were reassessed to establish historical distributions as of 2012. This reassessment served two main purposes. Firstly, species that were on the original Redmap list prior to Australia-wide expansion of the project in late 2012 (i.e., all species from the Tasmania region) had historical distributions assessed in 2009, rather than 2012 as for non-Tasmania target species. Secondly, access to ecological data has greatly increased over the past decade, with more historical datasets becoming publicly available through centralised databases. Further, historical species records are sometimes revised or recently emerge (e.g., with the identification of historical museum specimens), causing flux in species' known distributions over time. Our 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.

Species historical distribution reassessment was conducted as follows. From each species' Australian Faunal Directory (AFD; ABRS 2009), webpage (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 dates that species' pages were last updated) were extracted and the distribution description was converted to a latitudinal (or longitudinal, for distribution limits on the south coast) extent for each species, and a range of key Australian regional distributional references and checklists were similarly consulted (e.g., Edgar 2008; Gomon et al. 2008; Hutchins and Pearce 1994; Hutchins 2001; Hutchins and Swainston 1999; Johnson 2010; Kuiter 1993; Kuiter 1997; Last et al. 2011; see Data S1) along with those identified through species-specific searches within scientific literature databases. In cases of broader distributions reported from species AFD pages last updated between 2013 and the present, 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 species occurrences in the expanded range existed prior to 2013. The Australian National Expert Fish Distribution (FishMap) maps including 172 of the target species (last updated largely between 2008 and 2012), were consulted as shapefiles (available at https://www.marine.csiro.au/data/caab/). However, they were not used as definitive distribution references as the degree to which the maps reflect the extent of observational data versus depth-based modelled ranges beyond the geographic extent of occurrence records cannot be discerned. The most conservative (i.e., most poleward) range limits identified from reference material were preliminarily reassessed as species range limits.

For species for which recent citizen science observations would putatively be out of range, reassessment was continued by reviewing species occurrence datasets in case pre-existing historical data which would expand known distributions poleward had not been included in distribution assessments as of 2012. This was conducted primarily through the Atlas of Living Australia (ALA) Spatial Portal (https://spatial.ala.org.au) which collates a range of georeferenced biodiversity datasets for the region including museum collections, dive surveys and fisheries data (see *References* in Data S1 for a full list), resources that can be leveraged to document historical species distributions (Booth et al. 2011). Historical biodiversity records poleward of the distribution heretofore documented from reference material were assessed through investigation of occurrence metadata, and where relevant, the data source material and/or relevant institutional personnel were contacted for verification. For commercially harvested species, catch distribution data were reviewed through Status of Australian Fish Stocks reports (https://www.fish.gov.au/) where available. Finally, citizen science observations from databases made prior to 2013 were incorporated in reassessed species historical distributions where they would expand species' distribution limits (or suggest evidence of range extensions that were underway prior to 2013).

2.6 | Data Analysis

Validated citizen science species records and historical distribution limits were used to identify out-of-range species occurrences as follows. For each species, a geographical limit poleward of which records were considered out-of-range was created by adding a 20 km buffer poleward of the latitude (or longitude for east–west extensions) of the historic distribution limit. The 20 km buffer was used to mitigate against spuriously identifying sightings as out-of-range if very close to the historical distribution, because small amounts of imprecision in historical range descriptions or the geographical coordinates of citizen science/historical occurrences would have an outsized effect on the results for short-distance putative range extensions (see Table S1). Identified out-of-range sightings for each species were then assessed with the decision tree described in *Assessment Methodology*.

To assess the relative contributions of the three citizen science data sources to detect marine range extensions, the number of target species represented, total number of observations of target species, and median number of observations per species were calculated and compared among sources. This assessment was undertaken both for all observations and only out-of-range observations. Totals across all datasets for each metric were calculated after removal of duplicate records as described in *Data quality verification*.

To examine geographic patterns among potential species range extensions, assessed range extensions were compared between broad eastern and western coastal regions. The 'east' region encompassed the EAC dominated east coast of Australia, eastern Bass Strait and both north and east coastlines of Tasmania, while the 'west' region encompassed the Leeuwin Current dominated west and south coasts of Australia to approximately Wilsons Promontory, VIC. The total latitudinal or longitudinal

TABLE 1 | Summary of overall and out-of-range (observed poleward of historical range limits circa 2012) observations of Australian marine species on the target list from three citizen science projects.

	Redmap	Reef life survey[a]	iNaturalist	Total (unique[b])
Target species represented	151	156	175	197
Total observations of target species	1069	68,854	28,570	76,118
Median observations per target species	4	136	69	215
Out-of-range target species represented	62	37	15	73
Potential range extensions represented	62	15	40	76
Range extensions for which the database recorded the poleward-most sighting	54	3	19	—
Total out-of-range observations (all spp.)	143	44	122	292
Mean out-of-range obs. per range ext.[c]				
All recorded species range extensions	1.88	0.59	1.61	7.58
(only range exts. recorded by the project)	(2.3)	(2.93)	(3.05)	—

[a]Only includes species for which photographic evidence out-of-range was available (i.e., those also present in Redmap or iNaturalist data).
[b]May be less than the sum of metrics from each database as species were recorded across multiple databases, and sightings were filtered for species-location-date duplicates in and across databases.
[c]Treating range extensions of the three species recorded out of range on both the east and west coasts separately.

distance from the historical range boundary to the most poleward out-of-range observation of each species was calculated with the distHaversine function from R package *geosphere* (Hijmans 2024). For range extensions originating from the west coast that continued longitudinally along the south coast, the (latitudinal) distance measurement was continued eastward (longitudinally) at 35°S, 116°E (parallel to the latitudinal and longitudinal extent of the SW Australian coastline). The total distances of range extensions were also compared across confidence assessment levels and broad taxonomic groups (cnidarian, crustacean, elasmobranch, mollusc, and teleost). The overall confidence assessments of range extensions were compared among Australian states.

Finally, to assess the potential contribution of citizen science data for detecting early indications of marine species range extensions, the range extensions identified in this study were compared to those reported in the scientific literature through to the end of 2023. This was conducted as follows: first, among species for which Australian populations were known to the authors to be described in the literature as undergoing range extensions, the relevant sources were checked to determine whether recent citizen science sightings had not extended beyond the poleward extent described in the literature. Then, range extensions not identified as previously described were cross-checked against recent studies that report on multiple marine range extensions across the Australian region (e.g., Fowler et al. 2018; Gervais et al. 2021; García Molinos et al. 2022; Lenanton et al. 2017). For the remaining range extensions that were still not identified as previously described, a literature review was performed by searching Google Scholar with *[species name]* "range extension OR expansion" OR "*new record*" [*region*], where region was "Australia" (or a relevant state name) for articles published through 2023, including recent synonyms of species names. Results were manually filtered by title and abstract, and then text, when relevant to identify descriptions of recent range extensions. For each species' Australian population identified as undergoing a range extension in this study, we determined whether they were either: not previously reported to be undergoing range extension to the poleward extent reported here; previously reported to be undergoing range extension but based on the same citizen science data; or previously reported to be undergoing range extension to the same or more poleward extent based on other scientific data.

3 | Results

3.1 | Identification of Species Range Extensions

After filtering the citizen science databases for verified observations of target species, the final species occurrence dataset included approximately 76,000 non-duplicate out-of-range observations for 197 of the 200 target species (Table 1). The three species from the target species list for which there were no verified observations were Tropical Sawshark (*Pristiophorus delicatus*), Freshwater Sawfish (*Pristis pristis*), and Mozambique Seabream (*Wattsia mossambica*). Taxonomic uncertainty was identified for Little Bellowsfish (*Macroramphosus gracilis*), where the taxonomic relationship with the more broadly distributed putative congener *M. scolopax* is unclear (Hoese and Lockett 2017). Given this would affect the outcome of the assessment, the Little Bellowsfish was removed from consideration. Taxonomic uncertainty was identified for *Albula* sp. and the two *Trygonorrhina* species; however, sightings were beyond historical range limits for either congener in both cases, so these species were not omitted from assessment (see Table S4). Of the 196 remaining target species considered, 73 were recorded with photographic evidence of occurrence beyond their historical distribution limits (Table 1), including one cnidarian, two crustaceans, six elasmobranchs, two molluscs, and 62 teleost fishes. For two species (Old Wife *Enoplosus armatus* and Rock Blackfish *Girella elevata*), only extensions of adult life stages were

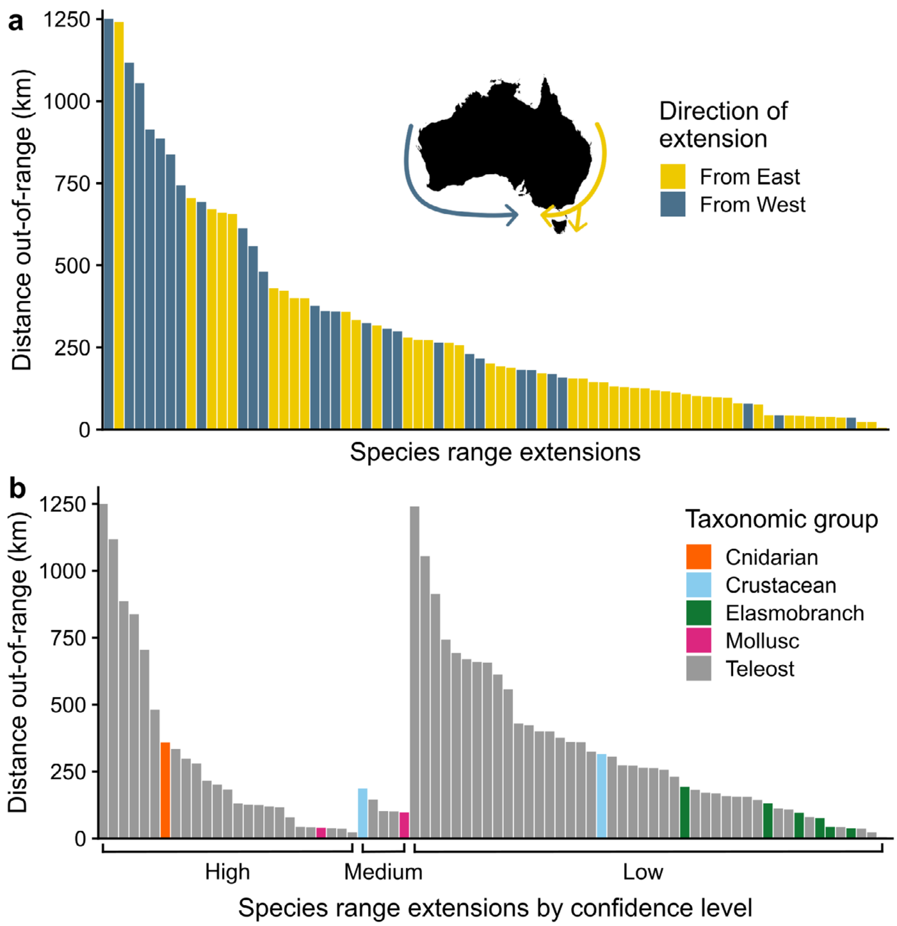

FIGURE 2 | Out-of-range distances (latitudinal, or longitudinal along the south coast) from historical (circa 2012) distribution limit to the maximum extent of validated citizen science observations, for 76 assessed marine range extensions around Australia. Regional extensions of a single species (e.g., along both WA and the east coast, four species) are treated separately. (a) Extralimital distance by direction. "From East" indicates extensions north-to-south on the East Australian Current-dominated east coast, and/or from east-to-west on the south coast. "From West" includes north-to-south range extensions originating on the Leeuwin Current-dominated west coast and/or from west-to-east on the south coast. (b) Extralimital distance by assessment confidence level and taxonomic grouping of the assessed species.

detected (i.e., into areas only itinerant juveniles historically occurred). For three species (Green Jobfish *Aprion virescens*, Barred Soapfish *Diploprion bifasciatum*, and Stout Moray *Gymnothorax eurostus*), sightings were recorded beyond both Australian east and west coast range limits, yielding a total of 76 potential range extensions: 49 on the east coast and 27 on (or presumed to be originating from) west coast populations (Table 1). Full details of each range extension assessed are available in Table S3.

3.2 | Comparison of Out-of-Range Sightings Across Citizen Science Databases

While the total numbers of target species present in each database were similar (between 151 and 175; Table 1), the Reef Life Survey and iNaturalist databases had approximately 64 and 27 times more total observations of target species than the 1069 recorded by Redmap (Table 1), reflecting the specialist focus of Redmap on unusual or out-of-range observations. While the generalist databases (RLS and iNaturalist) contained much greater numbers of total target species records, Redmap recorded the greatest total number of out-of-range observations (Table 1). Redmap also provided the widest representation of out-of-range target species (81.5% of the 73 total) and was the sole source of out-of-range observations of 32 range-extending species (vs. 10 only represented in iNaturalist observations). Redundancy of range extension detection across databases was limited, as only 10 species were recorded out-of-range by all three databases.

3.3 | Comparison of Range Extensions by Region and Confidence Assessment

The latitudinal (or longitudinal) extent of range extensions assessed from historical distribution limits to the maximum poleward extent of citizen science observations was mean 318 km, median 209 km, maximum extent was 1250 km (Figure 2 and Table 2). The minimum poleward extent was a 5 km range extension of Stout Moray *Gymnothorax eurostus* on the east coast, which, while within the 20 km buffer of the reassessed range limit, was included because the reassessed range limit (based on a 2006 citizen science record; Table S3) was a previously unreported poleward range extension of the species that exceeded 20 km prior to this study. The range extension distances of range extensions originating from the west were significantly greater than those originating from the east (Wilcoxon sign

TABLE 2 | Results of the qualitative range extension assessment of 73 marine species, listed alphabetically by genus. Numbers in the left-hand column correspond to those in Figure 3.

No.	Species	Standard name	Coast	Historical range extent	New extent	Confidence	Taxonomic group	Distance (km)
1	*Abudefduf vaigiensis*	Indo-Pacific Sergeant	W	32.03°S	33.668°S	High	Teleost	182
2	*Acanthocybium solandri*	Wahoo	W	128.25°E	140.28°E	Low	Teleost	1054
3	*Acanthurus lineatus*	Bluelined Surgeonfish	E	33.8°	36.26°S	Low	Teleost	273
4	*Albula* sp.	Bonefish	W	23.167°S	28.68°S	Low	Teleost	613
5	*Amphiprion biaculeatus*	Spine-cheek Clownfish	E	21.05°S	23.50°S	Low	Teleost	273
6	*Anoplocapros lenticularis*	Whitebarred Boxfish	W	144.617°E	145.03°E	High	Teleost	36
7	*Antennarius striatus*	Striate Anglerfish	E	36.667°S	37.58°S	Med	Teleost	102
8	*Aplodactylus lophodon*	Rock Cale	E	39.95°S	41.34°S	Low	Teleost	155
9	*Aprion virescens*	Green Jobfish	W	22.0°S	28.678°S	Low	Teleost	743
9	*Aprion virescens*	Green Jobfish	E	29.867°S	30.87°S	Low	Teleost	112
10	*Argonauta argo*	Greater Argonaut	E	43.139°S	43.50°S	High	Mollusc	40
11	*Arotrolepis filicauda*	Threadfin Leatherjacket	E	42°S	43.13°S	High	Teleost	126
12	*Auxis thazard*	Frigate Mackerel	E	40.5°S	41.40°S	Med	Teleost	100
13	*Caranx ignobilis*	Giant Trevally	E	34.15°S	35.44°S	Low	Teleost	144
14	*Centropyge tibicen*	Keyhole Angelfish	W	28.85°S	31.76°S	Low	Teleost	323
15	*Chaetodon auriga*	Threadfin Butterflyfish	W	32.03°S	33.55°S	Low	Teleost	169
16	*Chaetodontoplus personifer*	Yellowtail Angelfish	W	28.82°S	32.06°S	Low	Teleost	360
17	*Chromis hypsilepis*	Onespot Puller	E	42.75°S	43.13°S	Low	Teleost	43
18	*Coryphaena hippurus*	Mahi Mahi	E	40°S	43°S	High	Teleost	334
19	*Dactylophora nigricans*	Dusky Morwong	E	43.183°S	43.57°S	High	Teleost	43
20	*Dascyllus reticulatus*	Headband Humbug	E	30.2°S	33.8°S	Low	Teleost	401
21	*Diploprion bifasciatum*	Barred Soapfish	E	29.5°S	32.02°S	High	Teleost	281
21	*Diploprion bifasciatum*	Barred Soapfish	W	33.883°S	34.59°S	High	Teleost	79
22	*Enoplosus armatus* (a)	Old Wife	E	42.75°S	43.13°S	High	Teleost	42
23	*Epinephelus rankini*	Rankin Cod	W	28.483°S	33.49°S	Low	Teleost	558
24	*Epinephelus tukula*	Potato Rockcod	E	27°S	27.97°S	Low	Teleost	108

(Continues)

TABLE 2 | (Continued)

No.	Species	Standard name	Coast	Historical range extent	New extent	Confidence	Taxonomic group	Distance (km)
25	*Galeocerdo cuvier*	Tiger Shark	E	41°S	41.34°S	Low	Elasmo.	38
26	*Girella elevata* (a)	Rock Blackfish	E	41.274°S	43.08°S	High	Teleost	201
27	*Girella tricuspidata*	Luderick	E	42.99°S	43.20°S	High	Teleost	23
28	*Glaucosoma scapulare*	Pearl Perch	E	33.883°S	35.42°S	Low	Teleost	171
29	*Grammatorcynus bicarinatus*	Shark Mackerel	W	28.833°S	118.19°E	High	Teleost	886
30	*Gymnosarda unicolor*	Dogtooth Tuna	E	27.467°S	33.8°S	High	Teleost	705
31	*Gymnothorax eurostus*	Stout Moray	W	28.809°S	32.04°S	Low	Teleost	359
31	*Gymnothorax eurostus*	Stout Moray	E	33.8°S	33.84°S	Low	Teleost	5
32	*Heterodontus galeatus*	Crested Hornshark	E	35.733°S	36.9°S	High	Teleost	130
33	*Hippocampus histrix*	Spiny Seahorse	E	32.718°S	34.02°S	Med	Teleost	145
34	*Hyporthodus ergastularius*	Banded Rockcod	E	37.067°S	37.27°S	Low	Teleost	23
35	*Lates calcarifer*	Barramundi	E	23.467°S	27.26°S	Low	Teleost	423
36	*Lethrinus miniatus*	Redthroat Emperor	W	31.633°S	34.32°S	High	Teleost	299
37	*Lethrinus nebulosus*	Spangled Emperor	E	34.067°S	35.14°S	High	Teleost	119
38	*Lutjanus argentimaculatus*	Mangrove Jack	W	22.644°S	28.86°S	Low	Teleost	692
39	*Lutjanus johnii*	Golden Snapper	E	25°S	30.93°S	Low	Teleost	660
40	*Lutjanus quinquelineatus*	Fiveline Snapper	E	33.85°S	36.22°S	Low	Teleost	263
41	*Lutjanus sebae*	Red Emperor	W	28.878°S	33.19°S	High	Teleost	480
42	*Makaira nigricans*	Blue Marlin	W	118.228°E	131.43°E	High	Teleost	1250
43	*Melicertus plebejus*	Eastern King Prawn	E	41.283°S	42.97°S	Med	Crustacean	187
44	*Naso unicornis*	Bluespine Unicornfish	E	34.593°S	36.90°S	Low	Teleost	256
45	*Negaprion acutidens*	Lemon Shark	E	27.94°S	28.63°S	Low	Elasmo.	77
46	*Neotrygon australiae*	Bluespotted Maskray	W	28.717°S	28.33°S	Low	Elasmo.	332
47	*Octopus tetricus*	Gloomy Octopus	E	40.633°S	41.51°S	Med	Mollusc	97
48	*Parachaetodon ocellatus*	Ocellate Butterflyfish	W	28.75°S	32.13°S	Low	Teleost	376
49	*Parapercis ramsayi*	Spotted Grubfish	E	146.605°E	144.82°E	Low	Teleost	155

(Continues)

TABLE 2 | (Continued)

No.	Species	Standard name	Coast	Historical range extent	New extent	Confidence	Taxonomic group	Distance (km)
50	*Parma microlepis*	White-ear	E	144.62°E	144.21°E	Low	Teleost	36
51	*Parupeneus spilurus*	Blacksaddle Goatfish	W	33.637°S	117.23°E	Low	Teleost	264
52	*Pentapodus paradiseus* (a)	Paradise Threadfin Bream	E	33.83°S	34.07°S	High	Teleost	125
53	*Platycaranx chrysophrys*	Longnose Trevally	W	25.14°S	33.34°S	Low	Teleost	913
54	*Plectorhinchus lineatus*	Oblique-banded Sweetlips	E	24.11°S	27.97°S	Low	Teleost	430
55	*Plectroglyphidodon dickii*	Dick's Damsel	E	30.2°S	33.8°S	Low	Teleost	401
56	*Plectropomus laevis*	Bluespotted Coral Trout	E	27°S	145.11°E	Low	Teleost	1241
57	*Plectropomus leopardus*	Common Coral Trout	E	27.94°S	34°S	Low	Teleost	670
58	*Pocillopora aliciae*	Branching Coral	E	32.79°S	33.8°S	High	Cnidarian	358
59	*Pseudolabrus biserialis*	Redband Wrasse	W	123.8°E	136.050°E	High	Teleost	1117
60	*Pterois volitans*	Common Lionfish	W	32.02°S	33.96°S	High	Teleost	216
61	*Sagmariasus verreauxi*	Eastern Rock Lobster	E	140.7°E	137.19°E	Low	Crustacean	316
62	*Scarus ghobban*	Bluebarred Parrotfish	E	34.069°S	35.12°S	High	Teleost	117
63	*Scorpis georgiana*	Banded Sweep	W	136.1°E	138.64°S	Low	Teleost	230
64	*Seriola lalandi*	Yellowtail Kingfish	E	43.2°S	43.55°S	High	Teleost	39
65	*Siganus fuscescens*	Black Rabbitfish	W	32.2°S	33.63°S	Low	Teleost	159
66	*Stethojulis bandanensis*	Redspot Wrasse	W	32.03°S	33.66°S	Low	Teleost	182
67	*Trachinotus botla*	Common Dart	W	33.32°S	117.31°E	Low	Teleost	307
68	*Triaenodon obesus*	Whitetip Reef Shark	E	27.43°S	28.61°S	Low	Elasmo.	132
69	*Trygonoptera imitata*	Eastern Shovelnose Stingaree	E	40°S	40.87°S	Low	Elasmo.	96
70	*Trygonorrhina dumerilii*	Southern Fiddler Ray	E	41.15°S	42.88°S	Low	Elasmo.	192
71	*Xiphasia setifer*	Hairtail Blenny	E	37.45°S	43.35°S	Low	Teleost	657
72	*Zanclus cornutus*	Moorish Idol	W	24.50°S	32.03°S	High	Teleost	838
73	*Zebrasoma scopas*	Brown Tang	E	33.083°S	33.8°S	Low	Teleost	80

Note: Range extensions are presented separately for species observed out of range from both west coast and east coast Australian populations. Historical distribution limits in degrees latitude are the southernmost distribution limits, while those in degrees longitude are the westernmost distribution limits, unless presented in italics which denote easternmost limits. Extensions denoted with "a" pertain to only adult life stages extending into areas where previously, specifically only juvenile life stages were known to occur. Taxonomic group *Elasmo.* = Elasmobranchs. Full details are available in Table S3.

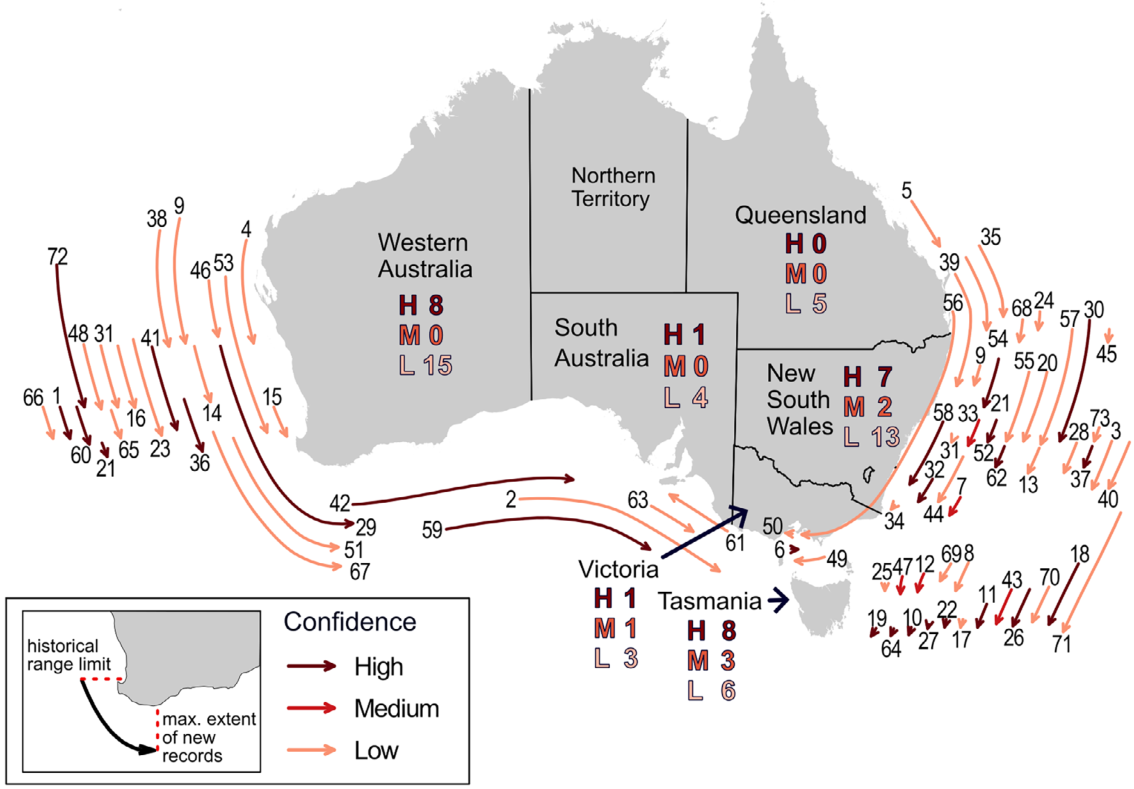

FIGURE 3 | Graphical representation of 76 assessed range extensions around the Australian coastline. Numbers correspond to species' numbers in Table 2. The beginning (without arrowhead) of each extension line represents the latitude, or on the south coast longitude, of the species' historical (circa 2012) poleward-most distribution limit in the region, and the extent of the arrow depicts the maximum latitudinal or longitudinal extralimital extent of recent out-of-range citizen science observations. The arrows are spaced vertically to allow differentiation of lines and do not represent distances from the coast. State names are displayed with the number of range-shifting species observed along each state's coastline, by confidence level (H = High; M = Medium, L = Low). See Table 2 for precise latitudinal/longitudinal extent of each species' historical distribution limits and recent observations.

rank location difference 200 km, 95% CI 103–309 km; $W = 1012$, $p < 0.001$; Figure 2a), and of the 10 farthest poleward range extensions, eight were off the west coast of Australia.

Western Australia had the highest number of identified range extensions (23) followed by New South Wales (22), Tasmania (17), Queensland (5), Victoria (8), and South Australia (6); (Figure 3). In total, 25 range extensions were classified with high confidence, five with medium confidence, and 46 with low confidence (Figures 2b and 3; Table 2). There was no significant difference between distances of range extension among the three confidence level classifications (Kruskal-Wallis rank sum test $\chi^2 = 3.66$, $p = 0.16$).

3.4 | Comparison With Recent Scientific Literature

Crosschecking identified range extensions against the contemporary scientific literature revealed 45 of the 76 (59%) were not previously documented, 24 (32%) were described previously, but based on the same citizen science data presented here (based on Redmap data: 19 by García Molinos et al. 2022, three by Lenanton et al. 2017, one by Stuart-Smith et al. 2018; one based on an iNaturalist record by DiBattista et al. 2022), and seven (9%) were previously described in the literature based on other scientific observations (Table S3).

3.5 | Development of Communication Tools

Assessment information for the three Australian states with the greatest numbers of range extensions (New South Wales, Western Australia, and Tasmania) was summarised for state-specific 'report cards' for public dissemination, and all range extensions identified were illustrated on a national poster summarising distribution changes in Australian waters (Figure 4; https://www.redmap.org.au/article/report-card/). These were co-designed with citizen scientists who contributed to the three databases used in the assessment.

4 | Discussion

Changes in species' distributions and the composition of ecological communities are one of the most pervasive responses to climate-driven ocean warming, as thermal habitat in areas beyond historical poleward limits becomes suitable enough to host novel species (Lenoir et al. 2020; Pecl et al. 2017). There is, however, great taxonomic and regional variation in the pace and magnitude of these

FIGURE 4 | Examples of public communication products (i.e., Australia-wide poster *left* and Australian State report cards *right*) developed from draft results of this study to demonstrate the utility of citizen science data for assessing species redistributions to stakeholder groups responsible for contributing these data. Full versions are available at https://www.redmap.org.au/article/report-card/.

range extensions and therefore highly variable ecological and socio-economic implications (Rogers et al. 2019). Here, we have demonstrated that citizen science observations can play a valuable role in the detection of species range extensions. Of 200 target species investigated, 73 were associated with verified photographic observations beyond historical distribution limits. Importantly, most (58%) of the range extensions documented here have not been previously documented in the scientific literature, and of those that had, the wide majority (77%) were based on the same citizen science observations presented here. This demonstrates that observations reported by the public play a key role in identifying and monitoring species range extensions.

4.1 | Regional Influence of Oceanography and Citizen Science Sampling Effort

There are notable differences between the current study and the existing literature on the topic. In their systematic review of Australian marine species redistributions, Gervais et al. (2021); (see Table S2) revealed a greater number of range extensions in Tasmania (77), compared to western (18) or eastern Australia (31), which was suggested to be partly due to research effort (see also Fogarty et al. 2019). In the current study, there were similar numbers of high and medium confidence range extensions in Tasmania (11), WA (9) and NSW (9; Gervais et al. 2021 excluded "vagrant, juvenile-only observations, non-overwintering or transient" extensions akin to those classed as 'low confidence' in the present study). Moreover, Gervais et al. (2021) reported farther range extensions along the eastern coast, but in our study, the out-of-range distances reported were generally greater along Australia's western coastline. Differences in range extension distances between east and west coastlines reported here may be related to the number of citizen science observations recorded along each of the coasts, and ultimately, geographical variability in the density of citizen science observers. Australia's population is highly concentrated in coastal urban areas, so perhaps it is not surprising that for example, seven range extensions were detected in or near heavily populated Sydney Harbour. The population is even more concentrated on the west coast than the east, with most people living in proximity to the Perth metropolitan area to the south and very low densities at subtropical latitudes and north. This difference likely contributed to the long extent of west coast range extensions reported here (e.g., if a species has been extending without detection along poorly sampled coastlines for longer than the extent of this study, recent poleward observations would appear to be farther from the known, outdated historical distribution limit). However, a considerable amount of citizen science monitoring likely occurs away from participants' normal abodes, for example during remote dive holidays and fishing trips, so population density may not be a sufficient proxy of citizen science sampling effort. Determining the spatial/seasonal distribution and intensity of opportunistic citizen science monitoring effort relevant to out-of-range species detection presents a challenge beyond the scope of the present study, but would allow for more quantitative insights (e.g., trends in species' abundance near range edges) into continental-scale biodiversity to be gleaned from these data sources. As such, this is a priority area for further research.

The Leeuwin Current is the longest coastal current in the world, flowing 5500 km along Australia's western and southern coasts (Ridgway and Condie 2004). It is likely not a coincidence that eight of the 10 farthest out-of-range species observations occurred from the Leeuwin-influenced west coast. The Leeuwin Current's flow of warm water to the south could facilitate long-distance range extensions by transporting marine animals during their planktonic larval stage (e.g., Indo-Pacific Sergeant, *Abudefduf vaigiensis*) or by facilitating migrations of adults (e.g., Shark Mackerel, *Grammatorcynus bicarinatus*). On the west Australian continental shelf, the Leeuwin Current bathes the Houtman Abrolhos island chain (~28.5°S) and Rottnest Island (32°S) in tropical water, creating mid- and high-latitude warm water refuges which may serve as 'stepping stones' for range extensions (Hutchins and Pearce 1994) and foci for citizen science sampling effort. Of the 27 range extensions identified on the west Australian coast, the Houtman Abrolhos and Rottnest Island were the localities of seven and six historical range limits or poleward-most recent citizen science observations, respectively.

The East Australia Current (EAC) is shorter than the Leeuwin Current, but it transports a greater volume of warm water (Wijeratne et al. 2018), which may be reflected in the greater number of shorter-range extensions on the east coast of Australia. The differences in characteristics of range extensions on the west and east coasts may reflect other differences between their dominant currents, such as seasonal variability, as the Leeuwin Current is strongest in winter and the EAC is strongest in summer and autumn (Wijeratne et al. 2018; Ridgway 2007).

4.2 | Quality Control of Citizen (and Traditional) Science Biodiversity Data

Relative to most biodiversity monitoring objectives, the risk of drawing erroneous conclusions is elevated when assessing the occurrence of out-of-range observations, because a single putative species occurrence record can influence the assessment of the likelihood of a range extension. As such, more stringent data quality control measures than are routinely implemented for ecological assessments are required. We required photographic evidence of out-of-range species that were manually verified by species experts for all identified range extensions. It is worth noting that errors are not confined to citizen science data; we identified several inaccuracies in historical biodiversity records that were corrected in collaboration with museum staff during our assessment. Several of these would have otherwise resulted in 'false negatives' due to species historical range limits being set farther poleward. For example, two Common Coral Trout, *Plectropomus leopardus* records from 1882 in the Sydney area, more than 600 km south of the established historical range limit present in the Online Zoological Collections of Australian Museums (OZCAM) database were subsequently reclassified as Eastern Wirrah, *Acanthistius ocellatus* by Australia Museum staff upon investigation. Similarly, a putative Golden Snapper, *Lutjanus johnii* specimen in the Australian National Fish Collection from Barrow Island, WA was confirmed to be misidentified in 1987 during the distribution reassessment.

An important issue for the use of public biodiversity data is the availability, level of detail, and accuracy of accompanying metadata. Records aggregated from faunal collections (e.g., OZCAM) are included in major biodiversity databases (e.g., OBIS/GBIF/ALA), but key details like life stage are not always present. Here, including the southernmost ALA records of *Aprion virescens* would have extended the species' east coast range limit by more than 500 km. However, on review, Australian Museum staff identified these as larval specimens, that is, irrelevant to the distribution of post-recruits. Similarly, the crowdsourced identifications of iNaturalist records were generally of high quality among the 'research grade' data uploaded to biodiversity databases, but our verification process still found several obvious misidentifications, spurious records and duplicates. Caution is needed when using large ecological and biodiversity databases, including careful data cleaning, verification and quality control processes tailored to project objectives and associated risks posed by misidentifications.

Establishing historical range limits was a significant challenge for the current study, even among some common species. The lack of systematically established distributional limits, or at least accurate and consistent baseline data, prevented more of Australia's estimated 48,000 species (Butler et al. 2010) from being included in our assessment. Here too, citizen science has unique utility. For example, iNaturalist records of Midnight Snapper, *Macolor macularis*, from the early 1970s off Heron Island, QLD, were reviewed during the historical range reassessment portion of this study (Taylor 2020). As this species was not noted in the later area checklists (Russell 1983; Lowe and Russell 1990), these 50-year-old citizen science records substantially redefined the known range boundary of *M. macularis* to the south.

4.3 | Maximising the Utility of Citizen Science to Investigate Species Range Extensions

Many of the species identified as likely to be undergoing range extensions in this study included those routinely targeted by fishers in their historical ranges (and some in extended ranges, such as Snapper, *Chrysophrys auratus* and Yellowtail Kingfish, *Seriola lalandi* in southeast Tasmania). As such, understanding population attributes such as age structure, growth, mortality, and reproduction is important for these populations in extended ranges when developing and refining strategies to sustainably manage and maximise the opportunities these 'new' species bring to a region, especially as these characteristics may vary at range edges (Lenanton et al. 2017; Champion et al. 2018; Graba-Landry et al. 2023). We have shown targeted citizen science programs are successful in identifying out-of-range species, but they also can raise awareness of novel species in the recipient environment (Pecl, Ogier, et al. 2019). However, keenness to report sightings of a given species to the platform tends to decline once knowledge of the novel species in an area becomes more commonplace in the early stages of a range extension, despite the ongoing importance of collecting data required for management. Our findings demonstrated that the generalist citizen science sources used provide potential complementarity with Redmap to this end (i.e., among the evidence for range extensions they yielded are presumably sightings that contributing citizen scientists did not realise were out-of-range). There is a range of citizen science program formats and scopes that can complementarily fill in data gaps for species that are known to be in a new location with sustained engagement, whether targeted at range-extending species or not. For example, among fisheries target species, detailed ecological and biological data can be derived from small-scale targeted research projects that engage recreational fishers that actively target recently established species for sample collection (e.g., Wolfe et al. 2020; Graba-Landry et al. 2022; IMAS 2023), or at much broader scope, smartphone apps used by fishers can provide data to assess whether population abundance is changing near distribution limits (McDonald et al. 2025).

Considering the importance and inherent challenges of documenting species range extensions in the marine realm along with the large number of people routinely observing and documenting wildlife in the oceans and along coastlines, there is substantial potential for citizen scientists to contribute effectively to the early detection of range-extending species (Robinson et al. 2015; García Molinos et al. 2022). Similarly, other studies have demonstrated the role citizen scientists can play in detecting introduced species (Encarnação et al. 2021; Middleton et al. 2021). Moreover, the value of citizen science is not limited to providing cost-effective data, but it also holds great potential to improve public climate change communication and engagement (Nursey-Bray et al. 2018; Pecl, Ogier, et al. 2019). Participation in citizen science can enhance trust among stakeholder groups, with positive implications for marine and coastal management (Kelly et al. 2019). As millions of Australians engage in marine recreational or commercial activities each year, there is considerable growth potential for marine citizen science to contribute to scientific and public knowledge of the marine environment (Martin, Christidis, et al. 2016). Thus 'report cards' that publicly disseminate the results of community-collected data can foster greater engagement of disparate marine resource user groups in marine stewardship and participation in citizen science, further expanding the opportunistic data collection that, as our results indicate, can effectively supplement resource-intensive traditional scientific surveys to improve biodiversity monitoring critical to informing anticipatory management and conservation in the face of ongoing and accelerating climate change.

The limited overlap between the range extensions detected by each of the three databases included in this study demonstrates how citizen science programs with different strengths can contribute uniquely to biodiversity monitoring goals like the detection of species range extensions. The broad scope of iNaturalist (and projects on the platform such as the Australasian Fishes Project) results in a vastly greater number of species observations from citizen scientists. These observations, even if not explicitly recognised as range extensions when reported, can still be valuable for research on the topic. Further, while data collection is unstructured, the platform has been shown to be effective at sampling local species richness relative to standard scientific surveys, including rare and cryptic species (Roberts et al. 2022). By contrast, as the scope of Redmap is focused on detecting out-of-range marine species, fewer total numbers of observations are collected than from the broad-scope projects; however, it excelled in target (i.e., suspected range extending) species detection. A likely reason for its success is brand awareness among marine stakeholders around Australia (Nursey-Bray et al. 2018) and, as such, it can capture observations from users that may not otherwise engage in citizen science programs. Finally, by training volunteer divers to a high standard and employing a structured data collection protocol, Reef Life Survey leverages additional data from citizen scientists, such as species abundance, density, and size data, and trends over time (Edgar et al. 2020).

5 | Conclusions

The consequences of climate-driven range-extending marine species in recent history around Australia have ranged from kelp ecosystem collapses due to barren-forming sea urchins (Ling 2008; Ling and Keane 2024), ichthyotoxic red tides (Hallegraeff et al. 2020), but also the development of new fisheries (IMAS 2023). The conservation and management implications of these phenomena are palpable. However, before the potential impacts of a new range extender can be ascertained and anticipatory conservation measures can be planned, the novel species must first be detected in recipient areas, preferably at the very earliest stage of range extension. Over 90% of the range extensions throughout the past decade reported here have not been reported independently of the data used for this study, demonstrating that citizen science projects can provide insights to this end that are both unique and complementary to traditional scientific sources. As range extensions are a primary ecological response to climate change not only around Australia but throughout the world's subtropical and temperate oceans, the value of citizen science for this effort is of global relevance.

To maintain the benefits and achieve the full potential of citizen science projects, appropriate logistical and scientific support is needed. Reassessing the historical range limits of the 200 species assessed here with a systematic and consistent approach took considerable effort. Australia has ~48,000 marine animal species, most of which are data poor. Nonetheless, given the ongoing and likely escalation of species redistribution, the distributions of a much larger group of species would need to be systematically assessed to provide reliable baselines from which to measure future change. A recent study (DiBattista et al. 2022) demonstrates how much potential utility can be harnessed from citizen science observations given a reliable detection baseline. By integrating verified museum records with both records from citizen scientists and structured surveys, the authors identified 89 new species in Sydney Harbour, NSW, a 15% increase over a similar timeframe to the present study. Similarly, a study that consolidated historical and modern citizen science records from New Zealand identified a notable increase in tropical species diversity and 17 new-to-New Zealand species (Middleton et al. 2023).

Given the pace of likely extensions reported here and redistributions elsewhere over the last 10 years (Lenoir et al. 2020; Poloczanska et al. 2016), expanding and updating baseline assessments of species' distributions would greatly increase the capacity to detect and understand shifts in species distributions. To this end, we have three recommendations for future efforts both in Australia and globally. First, a confidence or uncertainty estimate across assessed baseline distributions to account for data availability and quality. Second, linking assessed distribution maps to the observational data on which they are based. This would not only suggest data sources likely to identify out-of-range species in the future, but also streamline future reassessment (e.g., as historical species records are taxonomically revised). Finally, where possible, we recommend incorporating life stage information as metadata with species occurrence records to enable assessment of life stage-specific (i.e., recruits/overwintering subadults/mature adults) shifts in distribution (e.g., Miranda et al. 2019). This would allow opportunistic data like citizen science data to address questions across various stages of species redistributions (Bates et al. 2014).

This study provides further strong evidence of the pervasive nature of climate-driven species redistribution and of the concentration of these range extensions along Australia's southwest and southeast coastlines. Predictive modelling and an exploration of the mechanisms that drive or limit species redistributions (e.g., Champion and Coleman 2021; Davis et al. 2021b) are needed to further understand ecosystem level implications of multiple concurrent gains and losses of biodiversity within a given region. Lastly, providing public feedback is important to increase, or even retain, engagement with citizen scientists including fishers and divers. Critically, effective communication with participants not only facilitates ongoing contributions to scientific knowledge, but also fosters a sense of community and purpose among participants (Martin, Smith, et al. 2016; Kelly et al. 2019; Nursey-Bray et al. 2018).

Author Contributions

B.W.W. conceptualisation; Data Curation; Investigation; Visualisation; Writing – Original Draft Preparation; Writing – Review and Editing. C.C. conceptualisation; Funding Acquisition; Methodology; Writing – Review and Editing. T.G. investigation; Methodology; Writing – Review and Editing. J.B. data Curation; Investigation; Methodology; Writing – Review and Editing. M.A.C. methodology; Writing – Review and Editing. T.R.D. investigation; Writing – Review and Editing. S.F. methodology; Writing – Review and Editing. T.H. methodology; Writing – Review and Editing. F.J.H. methodology; Writing – Review and Editing. G.J. funding Acquisition; Data Curation; Investigation; Writing – Review and Editing. J.P.K. methodology; Writing – Review and Editing. S.K. investigation; Methodology. M.M. data Curation; Investigation; Methodology; Validation; Writing – Review and Editing. N.M. data Curation; Investigation; Methodology; Writing – Review and Editing. G.M. data Curation; Investigation; Methodology; Validation; Writing – Review and Editing. R.P. funding Acquisition; Writing – Review and Editing. K.R.R. data Curation; Investigation; Writing – Review and Editing. J.S. data Curation; Investigation; Methodology; Writing – Review and Editing. J.S.-S. conceptualisation; Data Curation; Investigation; Methodology; Writing – Review and Editing. J.W.T. investigation; Writing – Review and Editing. S.-A.W. methodology; Writing – Review and Editing. G.T.P. conceptualisation; Funding Acquisition; Supervision; Writing – Original Draft Preparation; Writing – Review and Editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the results can be found in Table S3.

Peer Review

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/ddi.70022.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.