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METHOD

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Introduced alien, range extension or just visiting? Combining citizen science observations and expert knowledge to classify range dynamics of marine fishes

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Abstract

Aim: Despite the unprecedented rate of species redistribution during the Anthropocene, there are few monitoring programmes at the appropriate spatial and temporal scale to detect distributional change of marine species and to infer climate- versus human-mediated drivers of change. Here, we present an approach that combines citizen science with expert knowledge to classify out-of-range occurrences for marine fishes as potential range extensions or human-mediated dispersal events.

Innovation: Our stepwise approach includes decision trees, scoring and matrices to classify citizen science observations of species occurrences and to provide a measure of confidence and validation using expert knowledge. Our method draws on peer-reviewed literature, knowledge of the species (e.g. contributing to its detectability, and potential to raft with, or foul, man-made structures or debris) and information obtained from citizen science observations (e.g. life stage, number of individuals). Using a case study of suspected out-of-range marine fishes in Aotearoa New Zealand, we demonstrate our approach to defining species' ranges, assigning confidence to these definitions and considering the species detectability to overcome the data deficiencies that currently hinder monitoring the range dynamics of these species. Our classification of citizen science observations revealed that six of ten species had out-of-range occurrences; one of these was classified as an extralimital vagrant, four species had potentially extended their ranges and one species occurrence was likely due to human-mediated dispersal.

Conclusion: The case study of marine fishes in New Zealand validates our approach combining citizen science observations with expert knowledge to infer species range dynamics in real time. Our stepwise approach helps to identify data deficiencies important in informing scientific inferences and management actions and can be refined to suit other data sources, taxonomic groups, geographic settings or extended with new steps and existing tools.

KEYWORDS
Alien species, biodiversity monitoring, biodiversity redistribution, citizen science, climate change, decision tools, marine biosecurity, marine fishes, range extensions, rapid assessment

1 | INTRODUCTION

The rate of species redistribution during the Anthropocene is unprecedented (Chen et al., 2011) particularly in the marine environment (Poloczanska et al., 2013; Sorte et al., 2010). The primary drivers of species movement around the globe are human-mediated introductions (Sorte et al., 2010; Walther et al., 2009) and climate change (Bellard et al., 2012; Pecl et al., 2017). In the ocean, the vectors of human-mediated movement of "alien" species (i.e. novel or non-native species introduced outside their past or present distribution and natural dispersal potential) include biofouling and ballast water associated with shipping, and intentional or unintentional releases through the aquarium trade (e.g. Currie & Parry, 1999; Hewitt et al., 2004). Climate-mediated movement refers to "range extending" species that are able to disperse and survive in new locations owing to changes in ocean circulation and temperatures (e.g. Sagarin et al., 1999; Stuart-Smith et al., 2018; Vergés et al., 2014). Human-mediated introductions of "invasive" or "pest" species (i.e. alien species that become problematic in their new location) have had devastating impacts on recipient environments and economies (Sala et al., 2000), and although climate-mediated range extensions do not yet have the same notoriety, they pose similar risks (Johnson et al., 2011; Sorte et al., 2010). For instance, several species undergoing range extensions have already had negative impacts on recipient ecosystems—competing with native species (Arrontes, 2002) and modifying community structure (Holbrook et al., 1997a; Holbrook et al., 1997b; Ling, 2008; Madin et al., 2012)—presenting environmental, economic and social challenges (Johnson et al., 2005; Pecl et al., 2017).

Given the potential for both human-mediated and climate-mediated species introductions to severely impact recipient ecosystems and local economies, considering both within one observation and risk evaluation framework would have several benefits. In particular, as the rate of climate-mediated species introductions increases, the resourcing of mitigation versus incursion responses and impact management may need to be revised. For instance, legislation regarding ballast discharge, hull fouling and the aquarium trade (e.g. MPI Import Health Standard. *Ornamental Fish and Marine invertebrates* 2017) would not have any bearing on climate-mediated range-extending species (Pyke et al., 2008). Rather, a focus on the management of species impacts on the recipient ecosystem may need to be prioritized (e.g. culling of the range-extending urchin *Centrostephanus rodgersii* in Tasmania, Sanderson et al., 2015). Furthermore, responsible climate change adaptation of local economies and cultural practices requires an understanding of the potential risks posed by climate change (Adger et al., 2013; Pecl et al., 2017) necessitating the identification and disentanglement of climate-mediated species introductions. Integral to such a unified approach is managers' ability to detect new species occurrences outside of their known range (i.e. out-of-range occurrences) and to infer the likely mode of introduction.

Confidently detecting out-of-range occurrences of species requires a thorough understanding of the geographic range that species occupy (Gledhill et al., 2015). Given that large areas of the marine realm remain under-surveyed (Hortal et al., 2015) and that marine species are often cryptic (Hubert et al., 2012), wide-ranging and highly mobile (e.g. Block et al., 2005; Bonfil et al., 2005), our knowledge of geographic distributions is far from complete (Appeltans et al., 2012; Hortal et al., 2015). Furthermore, delineating the boundary of a species' distribution where individuals are naturally more diffusely or patchily distributed (McCarthy et al., 2013) and are therefore difficult to systematically survey (Bates et al., 2014; Feary et al., 2013) is a renowned challenge. Nonetheless, defining range boundaries is fundamental in detecting out-of-range occurrences for species undergoing human-mediated and climate-mediated dispersal and inferring subsequent range dynamics (Urban et al., 2016).

Systematic surveys of species range extents and biosecurity monitoring are costly, time-consuming and often spatially restricted; hence, marine scientists and managers must often rely on diverse sources of knowledge (Delaney et al., 2008). For instance, mining existing datasets collected for other purposes such as fisheries data (e.g. Robinson et al., 2015) and museum collections (e.g. Cheung et al., 2013; Perry et al., 2005), and the use of opportunistic species occurrence records provided by the general public (e.g. Lenanton et al., 2017; Liggins et al., 2020). In particular, citizen science—the participation of citizens in the collection of data or the provisioning of local knowledge for the planning, development and execution of scientific research (Eitzel et al., 2017)—has been useful in increasing temporal and spatial data resolution, overcoming a lack of baseline data and detecting out-of-range occurrences in both terrestrial (Theobald et al., 2015; e.g. The Great British Birdcount, MonarchWatch.org) and marine settings (Pecl et al., 2019; e.g. Range Extension Database and Mapping Project [Redmap] Reef Environmental Education Foundation [REEF]; European Alien Species Information Network [EASIN]). However, even though citizen science data have proven utility in contributing towards scientific (e.g. Lenanton et al., 2017; Soroye et al., 2018) and policy outcomes (e.g. Delaney et al., 2008; Madin et al., 2012), it often varies in completeness and has inherent biases that require careful quality control and validation (Bird et al., 2014; Isaac et al., 2014).

Qualitative assessment tools can help harmonize unstructured species occurrence data and incomplete distribution data, with the input of expert knowledge (Bates et al., 2014; Robinson et al., 2015).

In particular, decision (or classification) trees have been used by regulatory authorities, scientists and resource managers across the fields of biosecurity (Drolet et al., 2016; Wotton & Hewitt, 2004), applied ecology and climate change science (Robinson et al., 2015). The intuitive, systematic routines of decision trees facilitate the interrogation of varied data, allowing researchers to apply knowledge or select the appropriate information at each step and to implement expert verification for quality control. For example, drawing on knowledge of species' biology and an expert "Technical Advisory Group," Wotton and Hewitt (2004) used decision trees to inform post-border responses to invasive species incursions in New Zealand waters, and researchers in ocean warming hotspots in the United Kingdom (Hiscock et al., 2004) and south-eastern Australia (Robinson et al., 2015) have used decision trees to validate citizen science observations with the input of specific taxonomic and regional expertise to identify range extensions. There is great flexibility in how these qualitative assessments can be applied, so each decision framework can be tailored to the specific research or management questions, as well as the data, knowledge and expertise available.

Here, we present a series of qualitative assessment tools that combine citizen science observations with expert knowledge to classify marine species occurrences as within or out of range, and as potential climate-mediated range extensions or human-mediated introductions. Our approach builds on methods developed for similar purposes (Pecl et al., 2019; Robinson et al., 2015), but bridges climate change biology and invasion biology, to provide a framework suited to range-extending species as well as introduced alien species. Through the inclusion of life stage information and the number of observed individuals, our method additionally provides a means to detect and track the arrival, as well as the establishment and population growth of range-extending species or introduced alien species. Our method is unique in considering seasonal variability in defining species' ranges and therefore the detection of out-of-range occurrences for migratory species as a result of phenological shifts. Furthermore, rather than uniformly classifying the range status of a species, we classify individual occurrences to infer the local range dynamics of a species, increasing the spatial and temporal resolution of inferences and providing baselines for future monitoring.

We use a case study focussed on potentially out-of-range marine fish species in Aotearoa New Zealand to demonstrate the utility of our method. Oceanic island nations, like New Zealand, are isolated from source populations of both range-extending and introduced alien species, yet they are reliant on vessel movements, the predominant vector of human-mediated dispersal. For these reasons, identifying the mode of species introduction, assessing the risk posed by climate change and determining appropriate management actions are particularly challenging. We demonstrate that with the input of citizen science observations and an expert panel our method can identify out-of-range occurrences of marine fishes in New Zealand, use individual occurrences to classify the local range dynamics of species and provide an indication as to whether the out-of-range occurrence has been climate- or human-mediated.

2 | METHODS

2.1 | Overview of method

Our approach (Figure 1) is designed to classify occurrences of any target species as: within known range, extralimital vagrancy (*juvenile individual observed outside of its known range*), potential range extension (*mature individual observed outside of its known range; or several juvenile individuals observed outside their known range*) or a range extension (*several mature individuals observed outside of their known range*). Specifically, our approach first requires characterizing the species known range (*i.e. extent of the species' typical geographic distribution*) including seasonal variation, if applicable (*i.e. extent of the species typical geographic distribution for a given season/s*) and assigning a measure of confidence for these defined spatio-temporal range boundaries (Step 1). In Step 2, a species detectability score is assigned using a method similar to that presented in Robinson et al. (2015), based on likely modes of encounter, the species abundance and conspicuousness. Species observations are then classified as within known range, extralimital vagrancy, potential range extension or range extension based on the observation information and their location relative to the defined spatio-temporal range (Step 3). To determine overall confidence in the classification of these observations, the species detectability score (from Step 2) and the measure of confidence in the species spatio-temporal range boundaries (from Step 1) are combined in Step 4. Last, observations that were classified as extralimital vagrancy, potential range extension or range extension in Step 3 are further examined to assess whether they may be the result of human-mediated introduction in Step 5.

The decisions and scoring of species in Steps 1, 2 and 5 can be informed by knowledge of the target species taxonomy, appearance, geographic range, life history traits and dispersal habits, for example, provided by available scientific literature, databases (e.g. WoRMS, http://www.marinespecies.org/; GBIF, https://www.gbif.org; FishBase, https://www.fishbase.de/) and an expert panel (see "Sources" in Figure 1). The formation of an "expert panel" will be dependent on the study context and target species, but could include professional scientists with specific taxonomic or regional expertise, citizen scientists, holders of traditional or local ecological knowledge, or natural historians (Johnson et al., 2017). The appropriate mode of expert knowledge elicitation will also vary according to the specific case study but could include methods such as face-to-face meetings and facilitated discussions, or electronic questionnaires that are collated to provide majority opinions. The input of the expert panel is required for each target species (i.e. expert input is roughly scaled by the number of target species), whereas the classification of individual observations of target species can be conducted by a non-expert using the qualitative assessment tools.

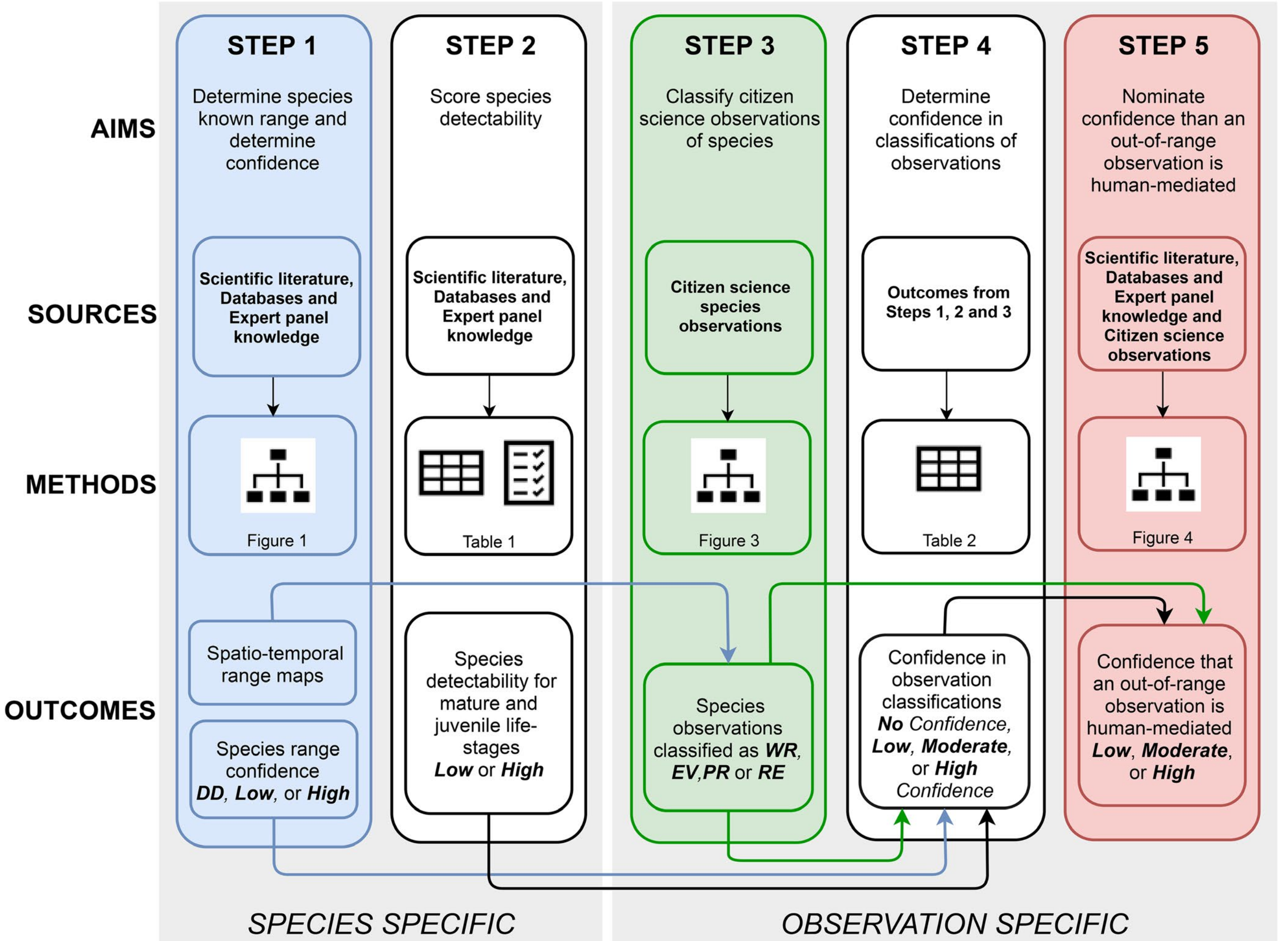

FIGURE 1 Overview of the approach to determine species' ranges, classify citizen science observations of species as out of range and whether they are due to climate-mediated or human-mediated dispersal. Steps 1 through 5 use several data and knowledge sources and qualitative methods, including decision trees (e.g. Step 1), scoring and matrices (e.g. Step 2), to provide species-specific and observation-specific information (background grey boxes). The outcomes from each step cross-inform each other and include rankings (e.g. "LOW," "HIGH") relevant to the aim of each step, or in the case of Step 3, a classification of the species occurrence is determined: within known range (WR), extralimital vagrancy (EV), potential range extension (PR) or range extension (RE). In Step 1, some species may be found data deficient (DD), and subsequent steps would not be undertaken

Below we describe and demonstrate the stepwise approach using a case study.

2.2 | Suspected out-of-range marine fishes in Aotearoa New Zealand

For our case study, New Zealand was defined as the entire coastline of the North and South Islands and all offshore islands within the Exclusive Economic Zone (excluding the Rangitāhua/Kermadec Islands, Chatham Islands and the Subantarctic Islands). We focussed on marine teleost fishes that have been described in publications as either "invasive," "alien" "vagrant," "occasional," "tropical," "subtropical," "rare" or "new-to-New Zealand." Marine fishes have been identified as effective indicators of local climate change impacts in other locations (Feary et al., 2013; Holbrook, Schmitt, & Stephens, 1997; Last et al., 2011), but there has been no concerted effort to consolidate knowledge regarding distributions of fishes in New Zealand and there is no national monitoring network. In our case study, Steps 1 and 2 were completed for 86 species to examine the method performance across species of varying biology, ecology and levels of expert knowledge. Ten species that represented the extremes in the potential outcomes of Steps 1 and 2, and for which there were varying numbers of species occurrences, were then selected to complete Steps 3 to 5 providing a diverse test and demonstration of our method. (For further information on target species selection, see Appendix S1.)

Occurrence data for these ten target species were collated from peer-reviewed literature including citizen observations (e.g. Francis, 2019; Francis & Evans, 1992; Francis et al., 1999; Roberts et al., 2017), unpublished occurrence records held by scientists, online databases (e.g. iNaturalist), social media (e.g. Facebook and Instagram), online forums (e.g. New Zealand Fishing forum and New Zealand Spearfishing forum) and other opportunistic

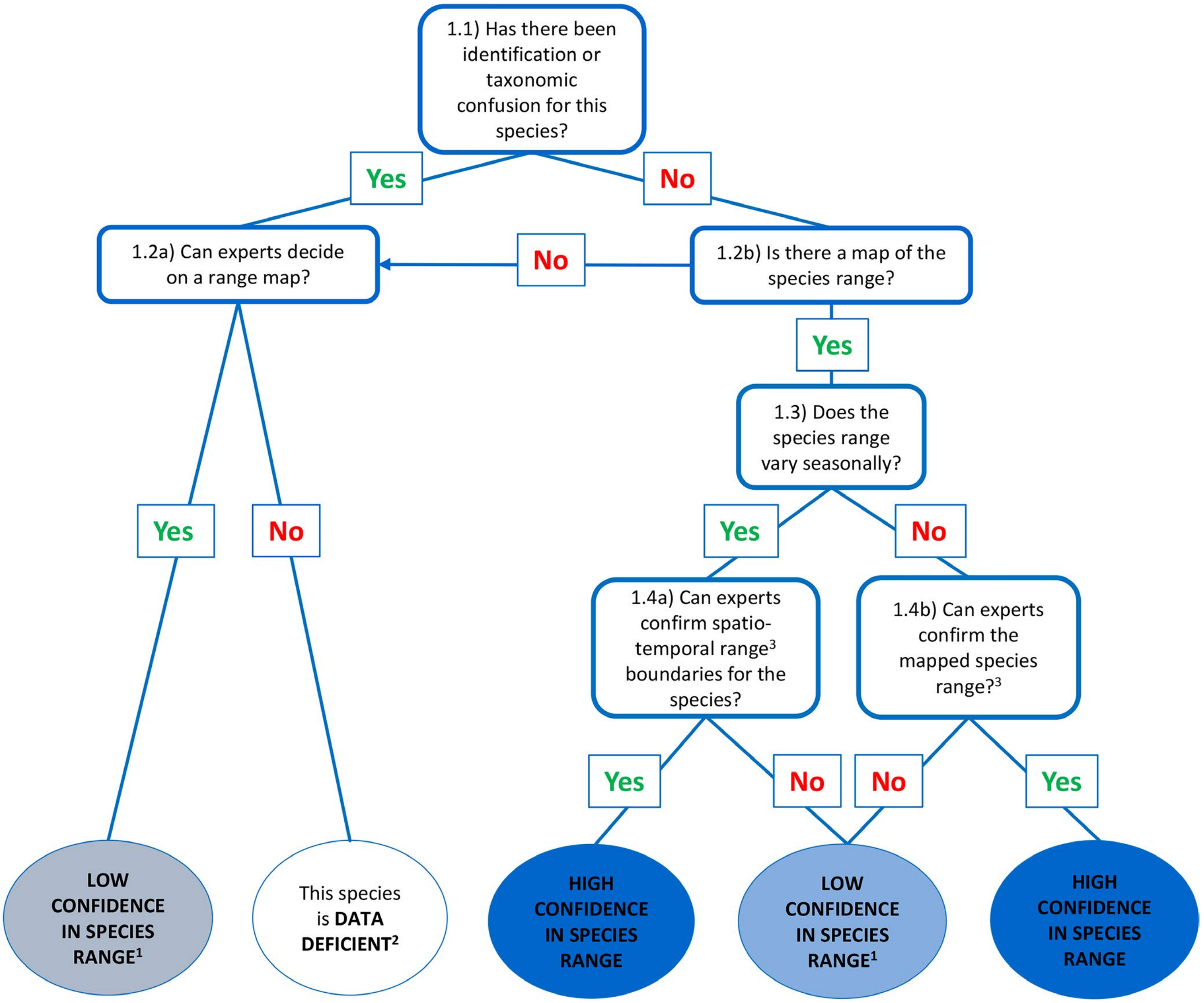

FIGURE 2 Decision tree for determining the spatio-temporal range of a species (*i.e. extent of the species typical geographic distribution for a given season/s*) and the confidence of the expert panel in the mapped species' range

observations from citizens (see: Appendix S2 for all occurrence data). Occurrence data spanned 1975 to 2019 and were quality-controlled prior to inclusion in the study (as described in Appendix S1).

An expert panel was formed to meet for a one-day workshop with subsequent email and verbal correspondence. Panel members consisted of New Zealand-based science professionals including marine scientists (four individuals, with a combined total of 350+ peer-reviewed publications on species biology, marine biosecurity and population dynamics in New Zealand and the South Pacific), experienced taxonomists (two individuals with >15 years' experience each and >1,200 combined citations) and resource managers (one individual with over 20 years' experience in fisheries regulation) representing eleven research institutions including universities, museums and government agencies. The panel also included experienced citizen scientists consisting of spearfishers (three active individuals with recognized observational expertise and over 50 years' combined experience), fishers (two active individuals that represent both commercial and recreational sectors and engage through published media) and SCUBA divers (three experienced divers and underwater photographers with recognized observational expertise and over 50 years' combined experience).

During the one-day workshop, the panel was broken into three subgroups and assigned a list of target species to work through Steps 1, 2 and 5. The subgroups were organized based on expertise (i.e. Fishing, SCUBA, Spearfishing) and were assigned species according to the mode by which the species was typically observed. Several species were assigned across multiple subgroups to determine whether there were subgroup biases and to increase overall confidence. All step outcomes were reviewed by the entire panel and final decisions were made by group consensus. A detailed description of all the steps that follow and the evidence/knowledge-based decisions pertaining to the case study is included in Appendix S1 and S3, respectively.

2.3 | Step 1: Determining the species spatio-temporal range and expert confidence

Determining known ranges is essential to set a baseline for classifying out-of-range occurrences; however, experts will have varying confidence in the data underlying the proposed baselines (Bates et al., 2014; Robinson et al., 2015). In our method, we use a decision tree to help describe the spatio-temporal range (i.e. extent of the species' typical geographic distribution including any seasonal variation) with specific relevance to the case study area and determine the collective confidence of the expert panel in the species' range/s (Figure 2). In the case of pelagic or highly mobile species, distinct spatial ranges would be described for relevant times of the year (e.g. capturing migration for feeding or reproduction).

For each target species, the panel first answered Question 1.1; whether there was any taxonomic or identification confusion that could affect our ability to accurately define the species' range. If a target species could be confused with a similar co-occurring species or there had been taxonomic confusion that may undermine knowledge of the species' range, the panel answered "YES" and moved to 1.2a. If the panel was confident there was no taxonomic confusion, they answered "NO" to Question 1.1 and moved to 1.2b.

To assist the panel in addressing Questions 1.2a and 1.2b, the authors constructed putative range maps for the target species in the study area using data sourced from the Ocean Biogeographic Information System (OBIS, www.iobis.org) and two New Zealand fish reference texts (Francis, 2012; Roberts et al., 2015). In assessing Question 1.2b, the panel verified and refined the putative range maps according to published resources and their own observations before moving to Question 1.3. If no mapped range was able to be sourced, the assessment moved to Question 1.2a. If the panel determined that the target species' range from Question 1.2b varied seasonally (Question 1.3), they were prompted to describe the spatio-temporal range of this species in Question 1.4a. If the target species showed no seasonal variability ("NO" to Question 1.3), the assessment proceeded to Question 1.4b, where the accuracy of the species' spatial range boundaries was determined. To summarize, the outcomes of Step 1 included a species' spatio-temporal range map/s and an associated measure of confidence in that range.

2.4 | Step 2: Scoring species detectability

Detectability of a species is a function of its natural abundance, habitat preference, morphology and behaviour (Robinson et al., 2015). Furthermore, the rate of encounter will be influenced by the species abundance in areas that are frequented by observers. In the case of easy-to-detect species, we might assume that the observations, and thus our classifications, more accurately represent their realistic occurrences and range dynamics. Conversely, for difficult-to-detect species, we have lower confidence in the accuracy of our classifications because it is likely that there will be unobserved occurrences. Similar to Robinson et al. (2015), the panel scored species detectability as either "HIGH" or "LOW" according to their likely method of detection, abundance and conspicuousness (Table 1). The method of detection for the target species was classified as either "fishing" (*species predominantly sighted as caught fish by commercial or recreational fishers*) or "underwater visual" (*species predominantly sighted* in situ *by divers, snorkelers, or spearfishers*) by the authors before the workshop and verified by the panel. Abundance was based on both the likelihood of encounter by observers (i.e. for underwater visual, how common the target species habitat is within diving range [rare = 1, occasional = 2, or common = 3]; or for fishing, how often a habitat is targeted by fishers [rare = 1, occasional = 2, or common = 3]) and the abundance of the target species within this habitat in its known range [rare = 1, patchy = 2, common = 3]). If the combined score was five or over, a species was considered "abundant;" if the score was less than five, a species was considered "not abundant" (Table 1). Because conspicuousness, and the ability for citizen scientists to observe individuals in situ (i.e. underwater visual) can vary significantly with ontogeny, we scored the conspicuousness of mature and juvenile life stages separately. To assess conspicuousness, a species was scored for the presence of each of the following physical and behavioural characteristics: maximum size 30 cm or larger =1, does not camouflage =1 and does not hide = 1. A species (or life stage) was deemed "conspicuous" if the total score was greater than or equal to two; if the score was less than two, it was deemed "inconspicuous" (Table 1). Abundance and conspicuousness were considered equal in importance when scoring detectability of underwater visual species; if either was "HIGH," detectability was also "HIGH." However, for fishing species, only abundance was considered as species are not observed in situ; if abundance was "HIGH," detectability was also "HIGH" (Table 1).

2.5 | Step 3: Classifying citizen science observations of species

A decision tree (Figure 3) was used to classify observations of target species as one of the following: within known range, extralimital vagrancy, potential range extension or range extension. By assessing each observation separately, we acknowledge that different parts of a species' range may be undergoing different range dynamics and that range extensions and species invasions can be stepwise (Bates et al., 2014). Thus, separate occurrences for the same target species may be classified differently but can be aggregated to form an overall view of the species range dynamics. The species' spatio-temporal range determined by the panel from Step 1 was used to determine whether the species observation was out of range (Question 3.1). If the observation was out of range, the species maturity was assessed (Question 3.2). Features of maturity vary among species but could include being of, or near, maximum size and/or reproductive size, mature colouration or spawning/nesting behaviour. In Question 3.3, the number of individuals observed was assessed. If mature individuals or two or more individuals were sighted during the same observation event, there is a higher probability of the species being

TABLE 1 Detectability scoring method (Step 2). (a) Abundance scoring for species observed predominantly by *fishing* and *underwater visual* observation, and (b) Conspicuousness scoring for species detected using *underwater visual* observation. A species (or life stage) was deemed "conspicuous" if the total score was greater than or equal to two; if the score was less than two, it was deemed "inconspicuous." The detection method, abundance and conspicuousness scores were combined to inform an overall level of "detectability" (c) for both mature and juvenile life stages of target species.

	Score
(a) Species abundance	
How commonly is the species habitat observed[a] or fished?[b]	
Rarely	1
Sometimes	2
Commonly	3
How common is the species in its habitat?[c]	
Rare	1
Patchy	2
Common	3
(b) Species conspicuousness	
Camouflage[d]	
Species exhibits some form of camouflage	0
Species does not exhibit camouflage	1
Body size[e]	
Maximum adult body size smaller than 30 cm	0
Maximum adult body size 30 cm or larger	1
Hiding[f]	
Species hides behind structures or within substrate	0
Species does not hide	1

(c) Detectability scoring

Detection method	*Abundance (a)*	*Conspicuousness (b)*	*Detectability*
Underwater visual	Abundant	Conspicuous	High
Underwater visual	Abundant	Inconspicuous	High
Underwater visual	Not abundant	Conspicuous	High
Underwater visual	Not abundant	Inconspicuous	Low
Fishing	Abundant	NA	High
Fishing	Not abundant	NA	Low

[a]In areas that observers in New Zealand may dive, spearfish, or swim. [b]Including recreational and commercial fishing in New Zealand waters. [c]Within the species' known range. [d]Camouflage includes background matching, self-shadow concealment, obliterative shading (countershading), and masquerade (leaf/other fish). [e]Body size was obtained from peer-reviewed literature, online databases, or expert knowledge. [f]If a species is known to hide, i.e., it generally conceals itself behind an object or inside cracks and crevices. Behavioural data were obtained from peer-reviewed literature or expert knowledge.

able to reproduce and/or persist and thus represent a range extension. These three questions (Questions 3.1, 3.2 and 3.3) were used to distinguish an out-of-range occurrence as extralimital vagrancy, potential range extension or range extension.

2.6 | Step 4: Determining confidence in the classification of observations

In some applications, a score of overall confidence in the classification of species occurrences may be helpful. Increased confidence in a species' spatio-temporal range gives greater confidence in the identification of out-of-range occurrences. However, a species' detectability also contributes to our overall confidence because it influences the likelihood that our knowledge based on observations accurately represents the species range and actual occurrence within a location. Thus, in Step 4, we combine species' range confidence (Step 1) and species detectability scores (Step 2) to provide an overall confidence in the classification of observations for that species (Table 2).

2.7 | Step 5: Determining confidence that out-of-range occurrences are due to human-mediated dispersal

Several potential pathways for human-mediated dispersal of marine species have been identified globally, including hull fouling, ballast discharge, the aquarium trade, aquaculture and intentional introductions (Lonhart, 2009; Rilov & Crooks, 2009). For out-of-range occurrences from Step 3, the panel assigned a level of confidence ("LOW," "MODERATE" or "HIGH") as to whether the occurrence may be the result of human-mediated introduction (Figure 4). To do so, we assessed if the species' known range was contiguous with the out-of-range occurrence, where the assumption is that human-mediated introductions lead to discontiguous species' ranges (Question 5.2). We also determined whether the observation occurred in an area of anthropogenic activity such as ports, wharves or popular anchorages (assessed in Question 5.3; as per Chapman & Carlton, 1991; Sorte et al., 2010). These are likely areas of higher vessel movement, which in turn increase the likelihood of species introductions by way of hull fouling, bilge or ballast water discharge. In addition, regardless of whether the occurrence was in an area of high human use or not, the propensity of a species to raft with, or foul, man-made structures or debris was assessed (Question 5.4a,b). These traits are known to heighten the risk of human-mediated introduction and such vessel and debris movements are known to have introduced marine species to areas remote from centres of anthropogenic activity (Francis et al., 1999; Willis et al., 1999; Wotton & Hewitt, 2004). Last, in Question 5.5, we consider whether the species is included in the aquarium trade and could have been released in areas of high human use (i.e. when we answered "YES" to Question 5.3).

3 | RESULTS

A total of 86 species were scored for range confidence (Step 1) and detectability (Step 2) by the expert panel during the one-day workshop. Thirty-three of these species were independently scored by more than one subgroup to address observational and expert

FIGURE 3 Decision tree for classifying species observations as within known range, extralimital vagrancy, potential range extension or range extension using the spatio-temporal range determined by the expert panel in Step 1

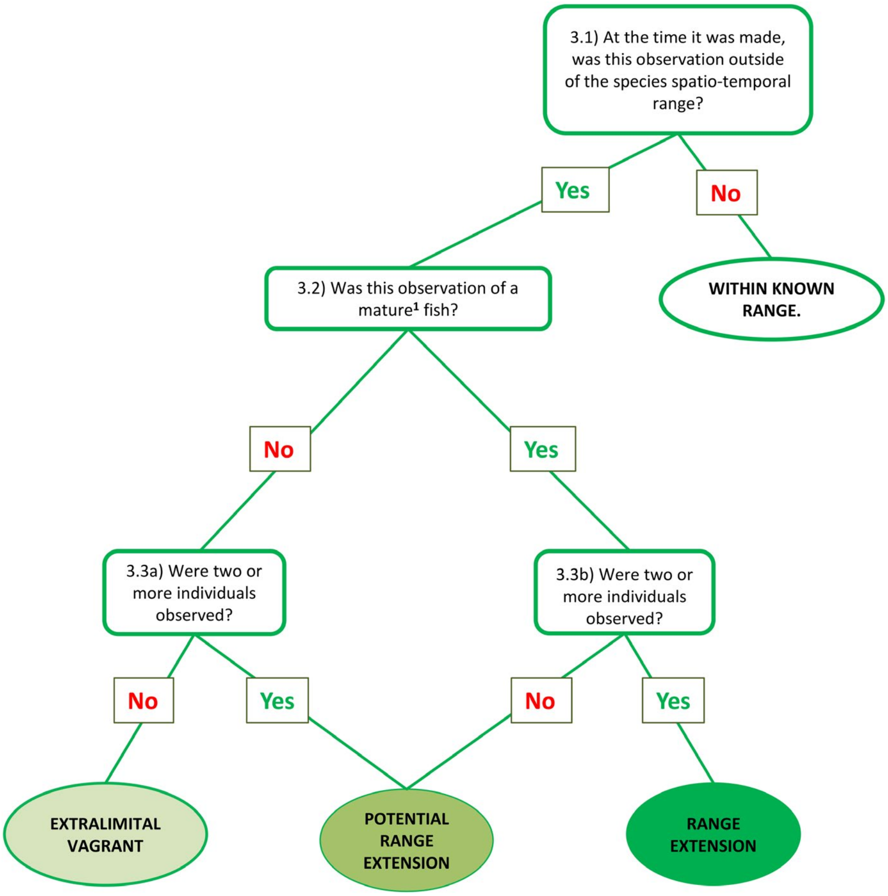

TABLE 2 Confidence scoring method for the classification of observations (Step 4). Overall confidence scores are a function of the spatio-temporal range confidence (Step 1) and detectability (Step 2). Range confidence can vary seasonally (i.e. a summer range and a winter range) and/or across life stages (i.e. juvenile and mature)

		Step 1: Spatio-temporal range confidence	
		LOW	HIGH
Step 2: Species detectability	LOW	NO Confidence	MODERATE Confidence
	HIGH	LOW Confidence	HIGH Confidence

bias before the panel made a consensus decision. For Step 1, the panel could not determine a spatio-temporal range, or could not reach consensus for an appropriate spatio-temporal range, for 25 species (29%), deeming them data deficient. For 13 (52%) of these species, identification or taxonomic confusion (Question 1.1 in Figure 2) contributed to their data deficiency, and for 12 species (48%), there was no range map available (Question 1.2a). Most of the data deficient species (80.2%) were predominantly observed in situ (i.e. underwater visual species). These 24 data deficient species were excluded from further assessment steps. For the remaining 62 species, the expert panel defined spatio-temporal ranges with "HIGH" confidence for 35 species (56%) and "LOW" confidence for 27 species (44%), with 16 species (27%) having species ranges that varied seasonally (Question 1.3). Most species for which there was "HIGH" confidence in the spatio-temporal ranges were underwater visual species (95.2%; see Appendix S4 for supplementary results).

In Step 2, the panel scored 24 underwater visual species as "HIGH" for detectability for both the juvenile and mature stages, 9 species as "LOW" for detectability for both the juvenile and mature stages and 15 with differing detectability scores across life stages (Table 3). For fishing species, the panel scored 5 species as "HIGH" for detectability for both the juvenile and mature stages, 6 species as "LOW" for detectability for both the juvenile and mature stages and 4 with differing detectability scores across life stages.

Before declaring a consensus, the most notable differences in the subgroup outcomes for Step 2 were the scores of the Fishers subgroup compared to the other two subgroups (SCUBA and Spearfishing; Table 3). The Fishers subgroup scored a larger proportion of the juvenile life stages as "conspicuous," and consequently, the detectability was also "HIGH," leaving no difference between the scored detectability of juvenile and mature life stages. These differences in initial subgroup scoring (and previously for ranges in

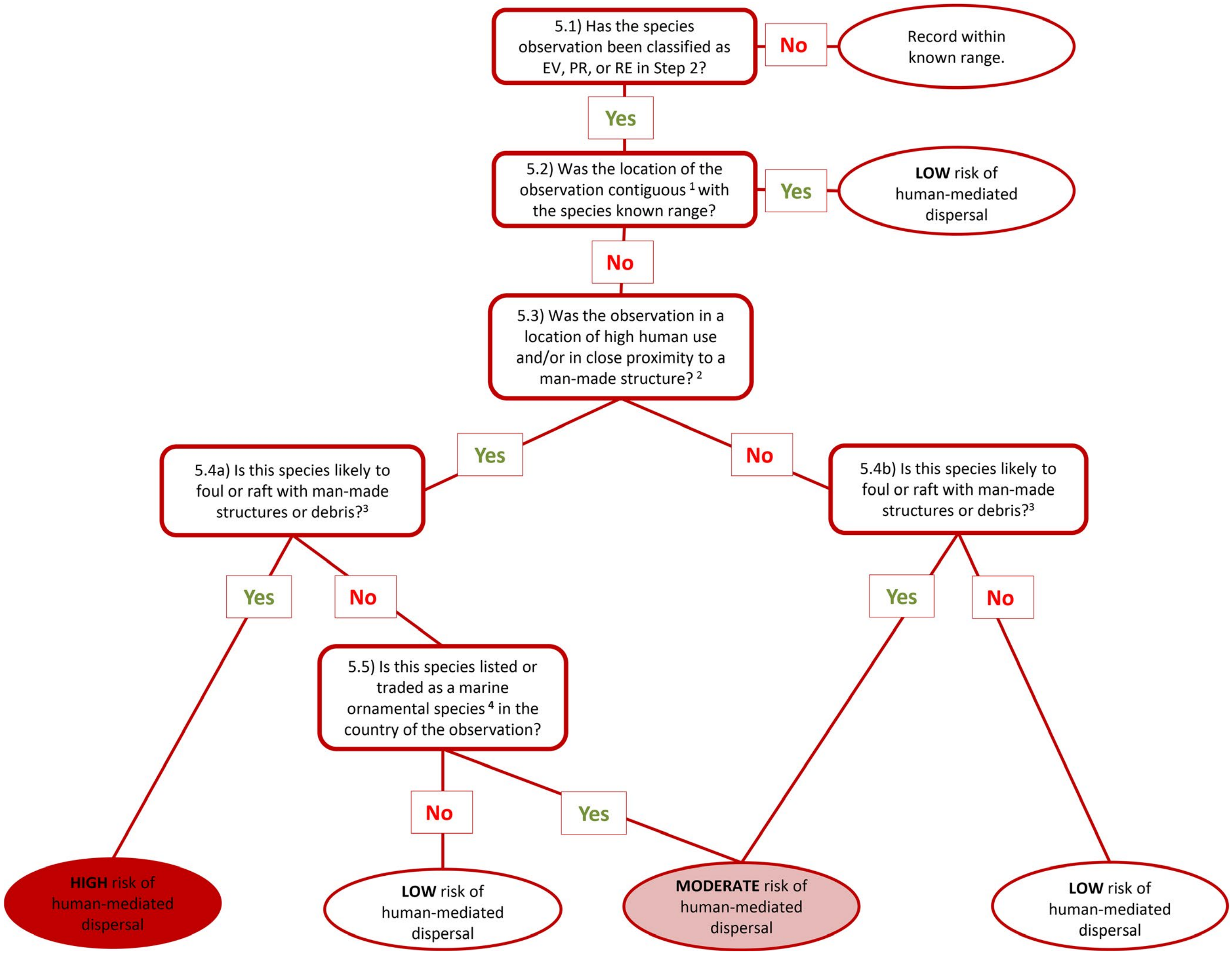

FIGURE 4 Decision tree for determining confidence in out-of-range observations classified in Step 3 (extralimital vagrant, potential range extension or range extension) as human-mediated

TABLE 3 Summary of the proportion of juvenile and mature life stages classified as abundant (i.e. "HIGH" abundance), conspicuous (i.e. "HIGH" conspicuousness) and highly detectability for target species assessed by more than one subgroup of the expert panel

			Juvenile		Mature	
Factor	Panel subgroup	Total number of species assessed (*n*)[a]	Low[b]	High[b]	Low[b]	High[b]
Abundance	Fishers	15	0.93	0.07	0.93	0.07
	SCUBA divers	13	0.77	0.23	0.69	0.31
	Spearfishers	27	0.96	0.04	0.81	0.19
Conspicuousness	Fishers	9	0.11	0.89	0.11	0.89
	SCUBA divers	13	0.54	0.46	0	1
	Spearfishers	21	0.52	0.48	0	1
Detectability	Fishers	9	0.11	0.89	0.11	0.89
	SCUBA divers	13	0.46	0.54	0	1
	Spearfishers	21	0.59	0.41	0	1

[a]Both "fishing" and "underwater visual" species were assessed for abundance; only "underwater visual" (species that are observed in situ) were assessed for conspicuousness.; [b]Abundance was "HIGH" if the score was ≥5; conspicuousness was "HIGH" if the score was ≥2; detectability was based on the method of detection, abundance and conspicuousness.

TABLE 4 Summary of results for the ten target species, including confidence in spatio-temporal range boundaries (Step 1), detectability (Step 2) and overall confidence in the observation classifications (Step 4). The proportion of the species observations classified within known range (WR), extralimital vagrancy (EV), potential range extensions (PR) and range extensions (RE) from Step 3, and the probability that the EV, PR or RE observations were facilitated by human-mediated dispersal (Step 5). Species that were data deficient or had no out-of-range observations are denoted by NA. Values or descriptions in brackets indicate results for juvenile stages where they differed from mature stages. For full step-by-step results, see Appendix S1 in Supporting Information

Species	Common name	Step 1: Range confidence	Step 2: Detectability		Step 4: Overall confidence	Number of citizen science observations	Step 3: Classification of observations (as proportions of total observations)				Step 5: Confidence in human-mediated dispersal (as proportions of total observations)		
			Juvenile	Mature			WR	EV	PR	RE	LOW	MOD	HIGH
Abudefduf vaigiensis	Sergeant major	LOW	HIGH	HIGH	LOW	9	0.75	0	0.25	0	1	0	0
Acanthocybium solandri	Wahoo	DD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Acanthurus dussumieri	Eye-stripe surgeonfish	LOW	LOW	HIGH	LOW (NO confidence)	20	0.93	0	0	0.07	1	0	0
Amphichaetodon howensis	Lord Howe coralfish	HIGH	HIGH	HIGH	HIGH	124	0.98	0	0	0.02	1	0	0
Cheilodactylus ephippium	Painted moki	HIGH	HIGH	HIGH	HIGH	34	1	0	0	0	NA	NA	NA
Chrysiptera notialis	Southern demoiselle	HIGH	LOW	LOW	LOW	3	0	0.33	0.67	0	1	0	0
Coryphaena hippurus	Mahimahi	HIGH	HIGH	HIGH	HIGH	59	0.94	0	0.02	0.02	1	0	0
Epinephelus daemelii	Spotted-black grouper	LOW	LOW	HIGH	LOW (NO confidence)	28	1	0	0	0	NA	NA	NA
Parablennius intermedius	Horned blenny	HIGH	LOW	LOW	MOD	1	0	0	0	1	0	0	1
Pomatomus saltatrix	Tailor	DD	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Step 1) were resolved through panel discussion and consensus before proceeding to Step 3.

The ten species selected for Step 3 spanned a broad range of habitats, life history, behavioural traits (see Appendix S1), likelihood of encounter, as well as varying levels of prior knowledge regarding the species in New Zealand. In the case of two species, Tailor (*Pomatomus saltatrix*, Linnaeus, 1766) and Wahoo (*Acanthocymbium solandri*, Cuvier, 1832), the panel could not confidently define their ranges in Step 1 (described above), so despite having citizen observations of the species, they could not be classified in Step 3 (Table 4). In the case of Tailor, an insufficient number of observed species occurrences prevented the panel from establishing the species' range in New Zealand. Although there were occurrence records for Wahoo, the high mobility of this species and mistrust of some of the data meant a consensus could not be reached regarding the range boundaries for this species in New Zealand.

The citizen science observations for the remaining eight target species were classified by the authors as within known range, extralimital vagrancy, potential range extension or range extension (Step 3; Figure 3). To provide a measure of confidence in these classifications, the panel's outcomes for Steps 1 and 2 were combined in Step 4 (Table 2). For two species, Painted moki (*Cheilodactylus ephippium*, McCulloch & Waite, 1916) and Spotted-black grouper (*Epinephelus daemelii*, Günther, 1876), all citizen science observations were within the species' known range (Figure 5). For Painted moki in particular, we had "HIGH" confidence in the defined range (Table 4), providing no evidence that the species' range is changing in New Zealand. We identified four species—Eye-stripe surgeonfish (*Acanthurus dussumieri*, Valenciennes, 1835), Lord Howe coralfish (*Amphichaetodon howensis*, Waite, 1903), Mahimahi (*Coryphaena hippurus*, Linnaeus, 1758) and Horned blenny (*Parablennius intermedius*, Ogilby, 1915)—that had occurrences classified as range extensions (Figure 5). For Lord Howe coralfish and Mahimahi, we had "HIGH" confidence that these occurrences represented true range extensions. Southern demoiselle (*Chrysiptera notialis*, Allen, 1975), Mahimahi and Sergeant major (*Abudefduf vaigiensis*, Quoy & Gaimard, 1825) also had observations that were classified as potential range extensions (Figure 5). We had the highest overall confidence in the out-of-range observations for Mahimahi and mature Southern demoiselle (Table 4; see Appendix S3 for supplementary results).

Finally, in Step 5 the panel assessed whether any out-of-range species occurrences were likely the result of human-mediated introduction (Step 5; summarized in Table 4). All decisions in Step 5 were made using group consensus, but there was no disagreement in outcomes among panel members. For the six species that had out-of-range occurrences, all occurrences were considered to be "LOW" risk of being facilitated by human-mediated introduction, except the sole occurrence of the Horned blenny (Table 4). Although we had "MODERATE" confidence that the observation of the Horned blenny represented a true range extension (Figure 5), we had "HIGH" confidence that this out-of-range occurrence was facilitated by human-mediated introduction (Step 5). This outcome was based on the propensity for members of the Blenniidae family to associate with biofouling, the fact that the observation of the species was on a man-made structure and in a location that was discontiguous with the known species range.

4 | DISCUSSION

Our approach draws on the strengths of expert knowledge and opportunistic citizen science observations to infer the range dynamics of previously unmonitored species. Here, we provide proof of concept for the method by classifying the range dynamics of several marine fishes in Aotearoa New Zealand. The ease of our approach and the intuitive outputs it produces should appeal to managers and science practitioners concerned with climate-induced biodiversity changes and the detection of alien species. Furthermore, the approach is modular and flexible and can be varied to enable application across different taxonomic groups and ecosystems and in combination with other existing tools. Below we highlight the novel features of our approach exemplified by our case study and discuss the methods performance based on: the diversity of target species we used, the extent of knowledge and data regarding these target species, as well as the expert panel formation and mode of elicitation.

Climate-mediated range extensions are often diffuse and difficult to differentiate from human-mediated species introductions (Sorte et al., 2010). Nonetheless, this distinction may be important for resource managers looking to monitor climate change impacts and/or detect dispersal pathways of alien species. For instance, New Zealand is heavily reliant on maritime transport of commodities and a popular destination for overseas recreational vessels, creating a significant pathway for marine species introductions through biofouling and ballast water (Coutts & Taylor, 2004; Dodgshun et al., 2007), yet novel species introductions are also known to occur via oceanic dispersal (Francis & Evans, 1992), and these are likely to increase in future (Molinos et al., 2016). The final step in our method (Step 5) helps discriminate between human-mediated introductions and climate-mediated range extensions. In our case study, we were able to determine that an observation of multiple mature individuals of the Horned blenny (*P. intermedius*) on a man-made wharf in northeastern New Zealand was likely to have been facilitated by human-mediated vectors (Figure 5). The detection of this species, and other human-mediated species introductions, helps to inform the appropriate practical responses of managers to out-of-range species occurrences (Bates et al., 2014; Weir & Salice, 2011).

Identifying specific types of change in species range dynamics, such as increased arrival, greater survival to maturity and seasonal changes in species' ranges (i.e. phenological changes), is critical in anticipating future biodiversity impacts. By including contextual information regarding the observation (i.e. season, maturity, number of individuals), our approach allows for the differentiation among the arrival (i.e. extralimital vagrancy), population growth and persistence stages (i.e. potential range extensions and range extensions) of introduced aliens or range extenders (sensu Bates et al., 2014). For instance, the pelagic Mahimahi (*C. hippurus*) is highly mobile and has

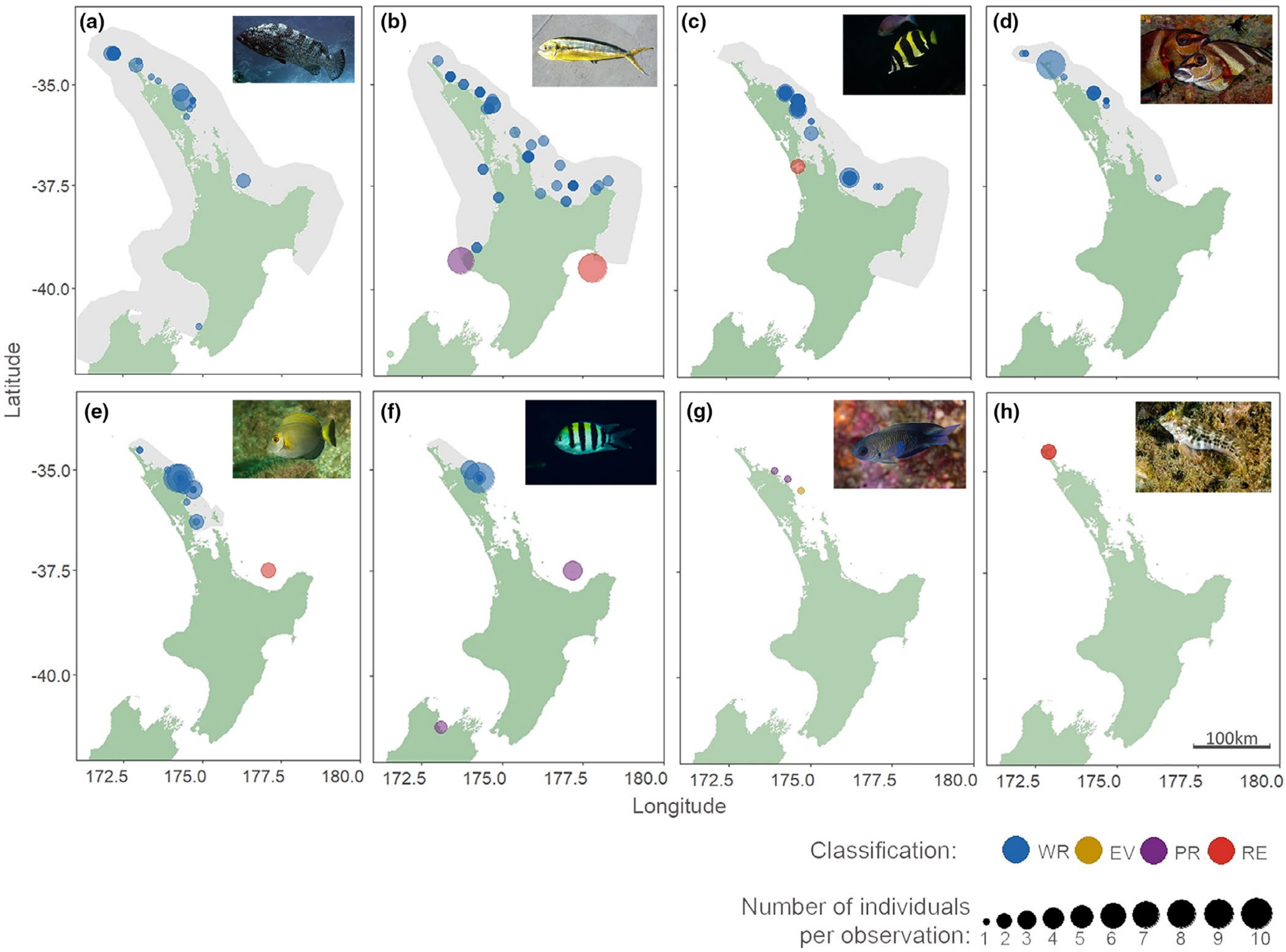

FIGURE 5 Observation classifications (within known range, WR; extralimital vagrant, EV; potential range extension, PR; range extension, RE; Step 3) for the target species where experts were able to define spatio-temporal ranges (grey shading; Step 1). (a) Spotted-black grouper, *Epinephelus daemelii*; (b) Mahimahi, *Coryphaena hippurus*: the species' range during the New Zealand summer season is shown, during the winter the species is largely absent from New Zealand waters; (c) Lord Howe coralfish, *Amphichaetodon howensis*; (d) Painted moki, *Cheilodactylus ephippium*; (e) Eye-stripe surgeonfish, *Acanthurus dussumieri*; (f) Sergeant major, *Abudefduf vaigiensis*; (g) Southern demoiselle, *Chrysiptera notialis*; and (h) Horned blenny, *Parablennius intermedius*: the expert panel determined that the species spatio-temporal range did not include New Zealand, and was confident that the species occurrence (classified as RE) was due to human-mediated dispersal (established in Step 5)

distinct seasonal ranges in high latitude locations (Norton, 1999). Sporadic occurrences of juvenile Mahimahi in New Zealand in summer are likely to be vagrancies, but our detection of several mature fish sighted outside of their spatio-temporal range represents range extensions (Figure 5). Through the precise use of observation information and the classification of individual occurrences, our method provides a means to continuously monitor species range dynamics, helping to detect real-time, spatially explicit range changes that aid in understanding the physical and environmental drivers of range dynamics.

Areas with a high incidence of marine range extensions have experienced devastating biodiversity and ecosystem changes (Ling, 2008; Pecl et al., 2017; Hawkins et al., 2009; Wernberg et al., 2011). Our method can help to highlight geographic areas where there is a high number of range-extending species occurrences (Figure 5), and, similarly to Lonhart et al. (2019), could be used to identify spatial hotspots for range extensions across several species. Most of the range extensions identified in our case study occurred within the north-eastern and Portland bioregions of New Zealand (Shears et al., 2008), regions where rare and vagrant species have previously been observed (Francis, 1996; Francis et al., 1999; Roberts et al., 2015). Continued monitoring could be prioritized in such regions to allow for the timely identification of new range extensions and their potential impacts and to inform management interventions.

The use of citizen science observations offers a cost-effective and growing opportunity to increase the scope and resolution of spatial and temporal data to monitor species range dynamics (Devictor et al., 2010). In our case study, all ten target species occurrences classified as potential range extensions or range extensions (Table 4) were made by citizen scientists and were previously unknown to the expert panel. Consequently, the inferences gained by the approach may be in part determined by the spatial and temporal patterns of citizen science observations (Bird et al., 2014). Although our approach cannot address range dynamics where there are no citizen science observations, the use of expert knowledge and published literature to cross-inform classifications reduces the risk of inferring out-of-range occurrences and changes in range dynamics erroneously where there are observations. For instance, in our case study, the proportion of out-of-range occurrence classifications was unrelated to the number of observations for the target species (Table 4).

The classification of species range dynamics, and confidence in those classifications, hinges on expert knowledge regarding the spatio-temporal ranges of target species (Step 1), their perceived detectability (Step 2) and propensity to be dispersed by humans (Step 5). For our case study, we formed an expert panel that maximized the breadth of knowledge across New Zealand and South Pacific fishes, as well as modes and geographic regions of encounter with these species. Owing to the diverse knowledge bases of the expert panel, frequently subgroups arrived at different outcomes for certain steps of the approach (Table 3). It is common practice to convene a panel of experts and ask them to produce consensus decisions (Johnson et al., 2017). In our case study, panel members were able to self-identify their weaknesses and support the evidence presented by other panel members to reach consensus decisions in most cases. Despite the diversity of expertise and willingness to reach an amicable consensus, our approach could not be applied to 29% of the target species because of a lack of knowledge and/or access to appropriate data (classified as data deficient). In this way, our approach has helped identify knowledge gaps that limit our ability to monitor the range dynamics of these species, helping to prioritize future research such as targeted taxonomic work or survey of underrepresented regions.

Using our approach, we were able to classify the range dynamics for a diversity of fishes, including benthic, pelagic and fished species, including those that varied in detectability. For our ten target species, their detectability did not affect the ability of the expert panel to determine their spatio-temporal ranges with high confidence; rather, the expert panel had "LOW" confidence in the spatio-temporal ranges of species with "detectability" scored "HIGH" (with the exception of juvenile Spotted-black grouper, *E. daemili* and Eye-stripe surgeonfish, *A. dussumieri*; Table 4). The classification of species occurrences was also not evidently influenced by the detectability of a species. For example, occurrences for two species that had "LOW" detectability (Southern demoiselle, *C. notialis* and Horned blenny, *P. intermedius*) were classified as potential range extensions (Table 4). Pelagic, migratory species were frequently data deficient due to a lack of information regarding their spatio-temporal ranges (e.g. Tailor and Wahoo), and based on discussion among expert panel members, co-occurring congenerics and conspecifics (e.g. Kyphosidae) are also likely to be data deficient using our approach owing to a lack of distinguishing features leading to taxonomic confusion.

The life history traits and questions included in our method are ubiquitous indicators for the ability of a species to extend its range in both marine and terrestrial systems. Furthermore, the steps of our approach may be easily machine-automated and refined to suit other data sources, geographic settings or complemented with new steps and existing tools (e.g. the Marine Screening-Level Risk Assessment Protocol for Marine Non-Indigenous Species [DFO, 2015]; Marine Fish Invasiveness Scoring Kit [MFISK], www.cefas.co.uk). For instance, the management response to an out-of-range occurrence is likely to be determined by the stage of establishment, species traits and the potential impacts of the alien species, regardless of whether its introduction has been climate-mediated or human-mediated. Such risk or impact assessments could be additional steps in the method, triggered when an out-of-range occurrence is indicated by our method. The value and utility of such a modular and stepwise approach may be particularly high when there are minimal resources available for continuous monitoring, and the expertise and information required must draw on several specialist or management groups and include stakeholder participation.

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PEER REVIEW

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DATA AVAILABILITY STATEMENT

Occurrence records for the ten target species used in the case study are provided in Appendix S2.

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BIOSKETCH

Middleton is a marine ecologist with a background in marine biosecurity, aquaculture, fish larval biology and a current research focus on tropical and subtropical fishes naturalizing in Aotearoa New Zealand. In partnership with Liggins, she leads the citizen science initiative "What's That Fish NZ?" (WTFNZ, https://www.facebook.com/WhatsThatFishNZ/). With the support of all co-authors, and the wider research and citizen science community, WTFNZ is consolidating distributional knowledge for Aotearoa's marine biodiversity, with the aim to provide a baseline from which to detect change and to engage the marine-going community in active research investigating marine biodiversity change.

SUPPORTING INFORMATION

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

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