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A holistic marine biosecurity risk framework that is inclusive of social, cultural, economic and ecological values

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ABSTRACT

Effectively managing non-indigenous marine species risks demands swift, transparent decisions amid limited data and in an environment where conflicting interest across environmental, economic, social, and cultural realms exists. Conventional risk assessment tools often fail to comprehensively evaluate these risks together, leading to stakeholder dissatisfaction, conflicts and poor biosecurity outcomes. To address this, we present a structured 7-step marine biosecurity risk framework. It systematically assesses incursion's ecological, economic, social and cultural impacts, encourages stakeholder engagement and promotes inclusive decision-making. Steps include defining contexts, setting objectives, estimating consequences, determining management options, evaluating trade-offs, implementing decisions, and communicating risks effectively. A simulation using *Sabella spallanzanii* illustrates its application. By integrating diverse perspectives and employing audience-centred communication plans, our framework facilitates informed and equitable decisions. It standardises data examination, aiding in addressing ecological, economic, social, and cultural integrity amidst non-indigenous marine species threats.

1. Introduction

Marine biosecurity management and governance encompasses both proactive (pre-border prevention) and reactive (post-border incursion) measures and responses, but often faces challenges such as limited data availability, uncertainty, unclear responsibilities and conflicting stakeholder values (e.g., [34,53]). To address these challenges, various marine biosecurity risk models have been developed, each with merits and limitations. Some focus on hazard identification (e.g., [17,29,69]), while others concentrate on quantifying border exposure and hazards (e.g., [31–33]). Additionally, certain models address post-border decision making (e.g., [5,41]).

Many risk models and frameworks prioritise economic values over environmental or socio-cultural values (e.g., [20,51,66]) due to the significance of economic imperatives in government decision-making. Alternatively, some models emphasise environmental or ecological risks to the exclusion of other values (e.g., [2,20,42,56]). A growing trend is the inclusion of cultural and social values (e.g., [8,9,15,26,32,37,53]) in risk models. However, few biosecurity risk models integrate all components to create a comprehensive framework that moves beyond pure science advice (such as [2]) to provide a pragmatic roadmap of a process with potential actions. Such holistic models focus on biosecurity management imperatives and aim to achieve "win: win" outcomes for both the environment and society (such as [37]).

New Zealand stands apart from many other countries in how it approaches biosecurity: NZ has legislated requirements to include cultural, social, economic, and environmental values within its biosecurity considerations (NZ Biosecurity Act). Hence, marine biosecurity frameworks developed in New Zealand should encompass these values (e.g., [34]). Embracing social and cultural values within risk frameworks allows for the identification and addressal of societal concerns in an open and transparent manner, reflective of a functional democratic society that enables voices of all relevant parties to be heard. However, integrating values across culture, social, economic, and environmental dimensions is complex, as these concepts span disciplines and may change over time and space.

This paper presents and describes the holistic biosecurity risk framework we have developed and provides several examples to

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illustrate its functionality. The approach provides an opportunity for consistency in decision-making. Our framework aims to provide a comprehensive and adaptive approach to marine biosecurity, facilitating better-informed decision-making and more effective risk management in this dynamic and critical field. This framework can be applied either pro-actively by gathering data in anticipation of an anticipated incursion or reactively by collecting information once an incursion has occurred. While we do not prescribe whether a pro-active or reactive approach is most appropriate, we emphasise that a-priori information collection, especially for high likelihood/high consequence invaders, enables faster responses and may lead more favourable outcomes. Additionally, having information and plans in place can enhance societal trust in decision-makers and decision making [62].

2. The marine biosecurity risk framework: holistic approach

In light of the challenges of integrating multiple values drawn from a plurality of voices, we have developed a marine biosecurity risk framework based on the principles of structured decision making [30]. This framework expands upon our previous risk frameworks developed for NZ biosecurity (e.g., [5,6]). Termed a "holistic biosecurity risk framework," it assesses consequences from a biosecurity event across economic, environmental, social, and cultural values, creating opportunities to examine trade-offs and synergies in the decision-making process. In this context, values refer to concepts or aspects that hold importance to people, tangible or intangible, recognised or not.

This risk framework builds upon established risk processes [63–65], and incorporates new quantitative data on values important to New Zealand citizens and residents (see [11,44,45]). Additionally, the framework integrates risk management and risk communication throughout its structure. Since biosecurity often involves crisis management and reactive decision-making in response to negative events, it is crucial to have information on societal values readily available enabling flexibility to adapt and iterate within the risk framework. Furthermore, incorporating societal values identified by the public, rather than relying solely on "expert" opinions, can foster and enhance social trust [60] and alleviate the perceived distrust of expert opinion that is prevalent in today's societies (e.g., [4,24,54,58,70]). Building trust in the evidence underpinning decisions can mitigate potential negative societal reactions to risk and improves opportunities for effective risk communication [38,46]. Blending expert insights with public values will likely result in more resilient risk management solutions (i.e., [61]) and enable effective risk communication.

Our risk framework consists of five interconnected decision points, encompassing six steps with a seventh overarching risk and decision communication step. Across this framework information is continuously fed into the process to inform each decision point and the decision and risk communications (Fig. 1). The information and decisions made at each decision point not only influence subsequent points but can also loop back to previous steps, allowing for iterative improvements and creating an adaptive framework. Throughout the entire process, risk communication is emphasised, promoting openness and information flow to all stakeholders. The five decision points are strategically linked across the six steps. For a pro-active application, the identification of an anticipated invader substitutes for a detection and the framework is employed to determine data needs and evaluate likely scenarios. For a reactive response they come into play once a non-indigenous marine species is detected, identified, and confirmed for that locality. To determine the species' origin (native or non-indigenous), we utilise the expanded criteria described by Campbell et al. [12], but other methods are available that are equally valid (e.g., [16,21]). Within this framework, we simulate an incursion of *Sabella spallanzanii* into Auckland Harbour, New Zealand, to illustrate examples of the framework.

2.1. *Sabella spallanzanii as a simulation*

Auckland Harbour is the major port in New Zealand and is in very close proximity to one of the main aquaculture regions (Hauraki Gulf). *Sabella spallanzanii* is native to the Mediterranean Sea and was first detected in New Zealand in 2008 [57]. It is a legislated "Unwanted Organism". It became a dominant biofouling species on aquaculture facilities [39] and it can raft to new locations of marine debris released from these facilities [10]. Biofouling at the aquaculture facilities is physically removed from mussel lines via a de-clumping machine [39]. The de-clumping process is optimised to reduce damage to mussels however the biofouling is often fragmented, and the debris is washed overboard into the Gulf waters [39].

Sabellids can also be cultured from fragmentation (e.g., [39,52]) with *S. spallanzanii* known to regenerate in native [47] and introduced populations [14,39]. Hence, the aquaculture de-clumping process has the potential to spread species such as *S. spallanzanii*. In general, annelids can replace lost or damaged body parts, Work by King [39] in New Zealand clearly demonstrates *S. spallanzanii* that are fragmented during the harvesting process and can regenerate from viable fragments.

2.2. *The marine biosecurity framework described*

By meticulously addressing the elements of each step and associated decision point prompts, the risk assessment process aims to improve outcomes by leading to guided, more informed, consistent, and sustainable management decisions regarding non-indigenous marine species (NIMS). Each step is described herein and is illustrated in Fig. 1. The framework can be used both pro-actively and reactively. We've noted at each step where pro-active collection of information can occur. We reiterate that what we describe below is based on a simulation that a *S. spallanzanii* incursion has occurred, been detected and taxonomically verified.

2.2.1. *Step 1: Clarify the decision context*

Identify how the non-indigenous marine species (NIMS) could have arrived (vector), where the NIMS came from (pathway), and its current distribution (local [including a delimitation survey], state, national and international). These tasks often occur in parallel. Determining the agencies that need to be involved in decision-making and what jurisdictional responsibilities need to be considered. Similarly, identify relevant parties that need to be informed and bought into the decision-making processes. As a collective, based upon the problem identification outcomes, and under consideration of regulations and legislation, decide what the endpoint of the risk assessment process should be. For example, is it a quarantine context?, can eradication occur?, or are no in-field/on-site management actions needed (take a watch and report stance)? A communication plan should be implemented or created if one does not already exist.

Components of Step 1 that are species and location dependent would occur reactively (once the incursion is detected). Information regarding identification of decision-makers can be established pro-actively, within import processes (e.g., [1,6]) for example, in alignment of regulations and policies (e.g., [16,28]), and within surveillance and operational response plans (e.g., [50]). When occurring reactively, information gathering and decisions need to be rapid and decisive (e.g., [12,55,71]).

2.2.2. *Step 2: Set objectives and measures*

The values that can be affected and/or need protection within the incursion zone(s) (geographic location where the NIMS has invaded and has established a population) are determined and potentially prioritised (use of weighting). Ideally, these values are mapped at a management applicable scale. How much impact is considered tolerable is determined to provide a threshold of acceptable change. Feasible timelines to mobilise a management action need to be considered. Immediate tactical timelines should be set, with either a scaling up or down of

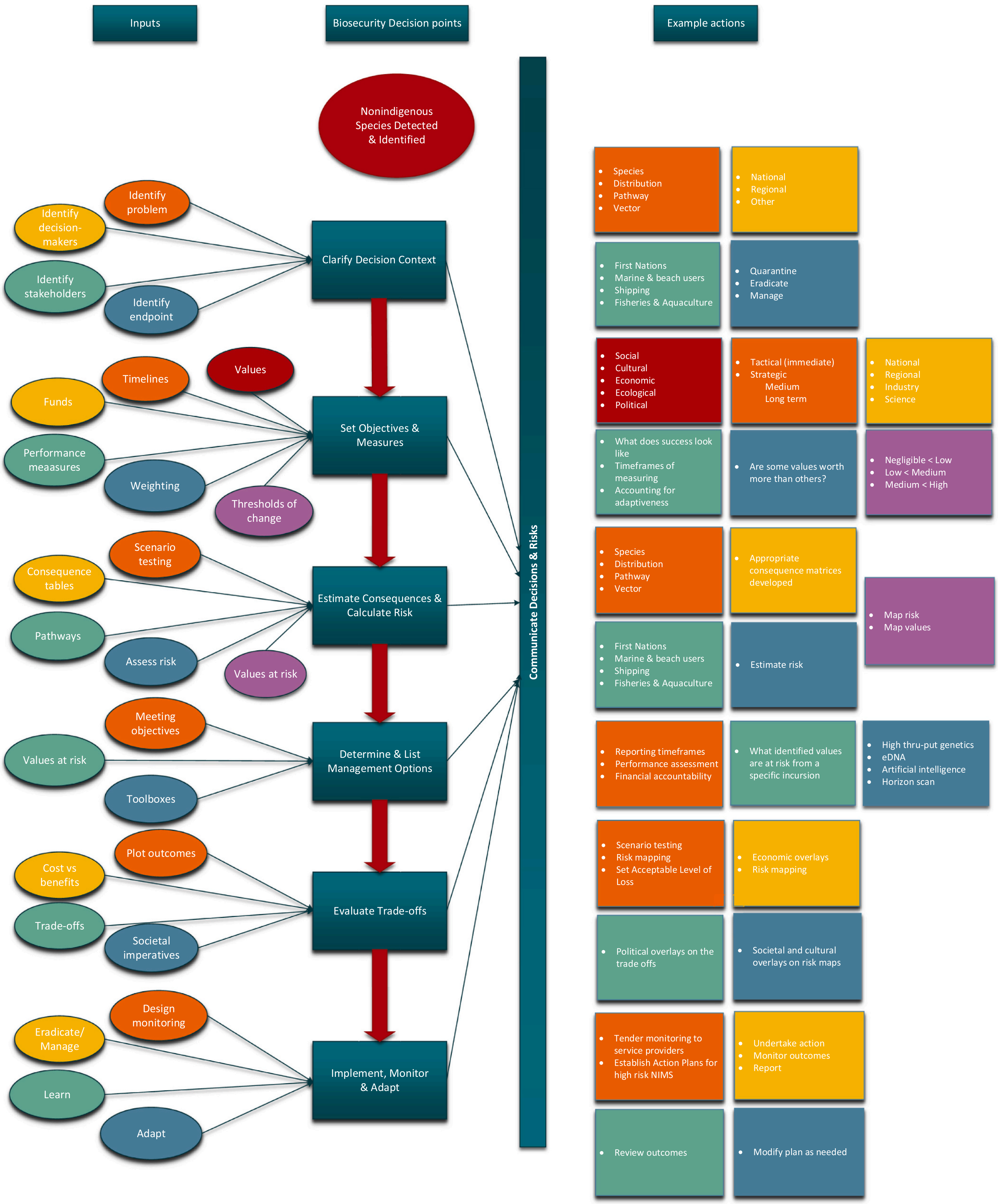

Fig. 1. Holistic biosecurity risk framework. Red arrows represent decision-points. Bubbles represent suggested data inputs needed to inform the decision making at each step. Bubble information can be gathered before an incursion occurs or afterwards during a response. Boxes represent example actions that can occur at each decision point. Bubbles and boxes are colour coded to provides examples specific to data input.

initiatives across the timelines. This information flows into medium and long planning timeframes. To support the response, funds to manage the incursion need to be identified. Management may expand across multiple sectors with different but aligned objectives for each sector. Careful consideration of the ability to eradicate versus long-term management, potential infrastructure impacts and needs, how sectoral behaviours can be managed (or altered if needed), and how stakeholder confidence can be rebuilt is needed. Based upon these considerations a set of objectives with performance measures are developed and communicated across management agencies and to relevant parties.

Within this step information such as identifying generic values, weightings of values, and acceptable thresholds of change can be collected before an incursion occurs. Other data inputs will be incursion specific and hence would need to be collected in a reactive manner or information that exists would be updated in the context dependence of an incursion.

2.2.3. Step 3: Estimate consequence and calculate risk (risk analysis)

Rapidly scenario test the incursion to determine probable actions with associated potential success. Information collected at earlier steps may be analysed at this step. Using *Sabella spallanzanii* as an example, consequence matrices (e.g., Supplementary material Tables S1-S3) and a risk matrix (Supplementary material, Table S4) would be developed, if not already available. The pathways of impact would also be determined, with stakeholder and community consultation, input, and consideration. Based upon the scenario testing and the consequence matrices, risk is estimated. Please note that the risk framework can start either before or after an incursion event occurs (NIMS detected and identified), therefore hazard identification (e.g., [28]) is not required and the likelihood is classified as "Almost Certain" (Supplementary material, Table S5).

Using *a priori* spatial mapping of values derived from a combination of qualitative and quantitative data facilitates rapid and informed assessment of potential consequences. By mapping values spatially (e.g., [36]), we can contrast them against the presence (or likely spread) and impact of species of concern. This process enables us to identify the subset of values that are likely to be affected by the introduction of a particular NIMS (Fig. 2). For instance, certain values may be present in locations or habitats where the NIMS is improbable to occur due to ecological or physiological constraints. Similarly, specific subsets of values may remain unaffected by certain species. For example, the northern Pacific seastar, *Asterias amurensis*, being a generalist benthic predator, is unlikely to directly impact the social value of recreational snapper fishing.

We note that the lack of comprehensive information on the potential impacts of many introduced species can hinder species management [22,32,53]. Never-the-less, the available knowledge and data can be used to create risk maps (Fig. 2). These risk maps, in turn, enable forecasting of probable impacts based on identified values (e.g., [11]) and potential spread, providing valuable input for management responses and resource allocations based on the consequences predicted by the assessment.

Incorporating spatially mapped values and risk forecasting within the risk framework ensures a proactive and targeted approach to marine

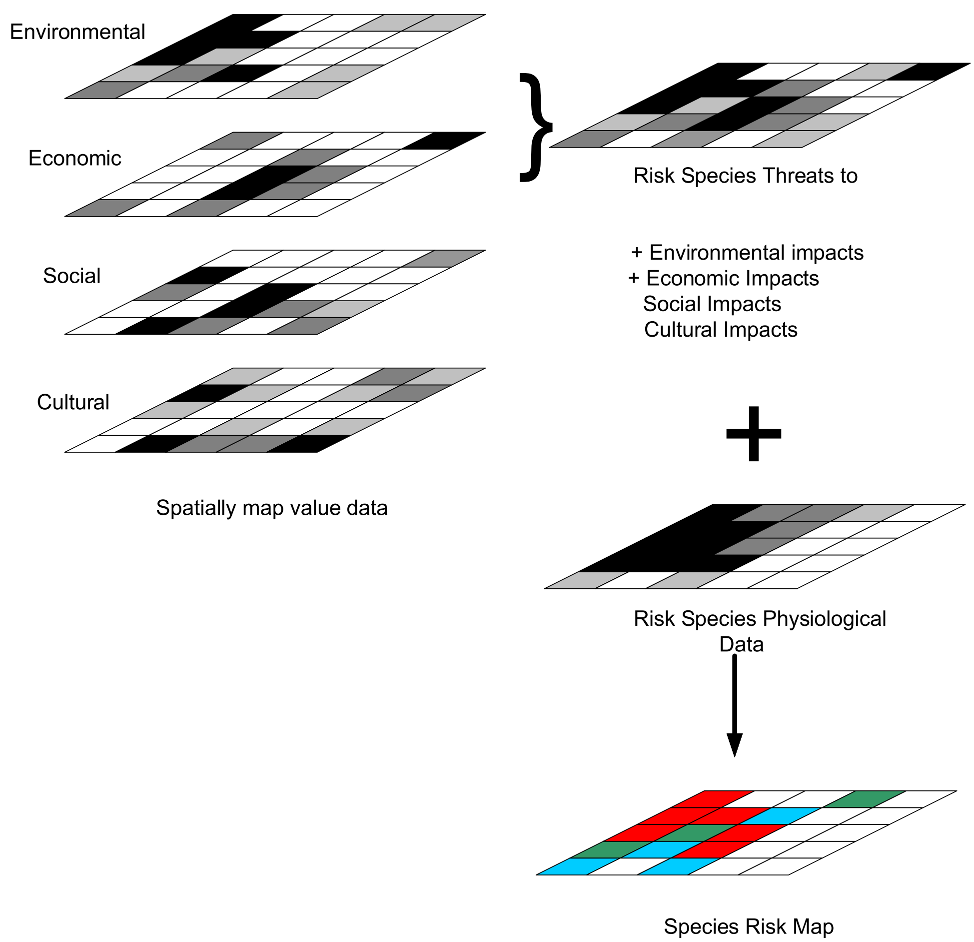

Fig. 2. Conceptual spatial risk map. The landscape is gridded into layers to enable the spatially explicit mapping of values (in this example, white denotes negligible or no value and black denotes high value), and the four value maps are then overlayed to produce mapped value data. The potential presence of a target introduced (risk) species based on physiological tolerance and ecological preference data provides a presence likelihood overlaid with values to then produce a species risk map (where white denotes low risk and red denotes catastrophic risk to the values present).

biosecurity management. By identifying areas of concern and potential impacts to specific values, decision-makers can allocate resources effectively to mitigate the risks posed by specific NIMS and safeguard marine ecosystems. Critical is that evidence in the form of the risk maps is now available to justify a decision.

As with Steps 1 and 2, aspects of Step 3 can occur proactively, such as using identified values to inform decisions. The risk assessment needs to occur reactively as aspects such as spatial distribution and hence potential impact on values will be incursion and species dependant. Establishment of consequence tables related to the values that are important to a region and/or legislated to protect can also occur proactively. Scenario testing and to determine potential consequences and assessing the risk is a reactive step that occurs.

2.2.4. Step 4: Determine and list management options

Based upon specific incursions, we can identify the values at risk and tailor management options accordingly. Step 4 is context and incursion dependant and hence components are reactive but may utilise information gathered prior to an incursion. Options can be categorised into strategic and tactical dimensions. Strategic approaches may involve the development of biosecurity toolboxes (eDNA and eRNA detection, CRSPR, and eco-engineering; e.g., [19,35,59]), investing in new technologies (e.g., AI/machine learning; [23,25]), and making adjustments to biosecurity frameworks, regulations, and policies (e.g., [3,28]). For example, during the black striped mussel Darwin incursion and response, data, tool, and policy deficiencies were identified and subsequently led to establishment of the Marine Pest Sectoral Committee (https://www.agriculture.gov.au/biosecurity-trade/pests-diseases-weeds/marine-pests/mp-sect-committee) and National Biosecurity Committee (https://www.agriculture.gov.au/biosecurity-trade/policy/partnerships/nbc), for example.

Tactical options include containment or eradication attempts (i.e., [3,27,43]), implementing or strengthening training, upskilling local communities, education and, or awareness programs and networks (e.g., [13,49,71]), or taking no immediate action and instead establishing monitoring programs. To ensure effectiveness, it is essential to regularly assess whether objectives are being met across different time frames and be prepared to adjust these objectives if needed. This process should be accompanied by set timelines for reporting information back to relevant parties.

2.2.5. Step 5: Evaluate trade-offs

Perform scenario testing and create risk maps for various management options. Explicitly, this step is reactive as it will be incursion and context dependant. Based on the results obtained, it becomes possible to establish an acceptable/unacceptable level of loss (e.g., [22,51,66]) within the context of risk management. This process includes developing cost benefit overlays to the risk maps (e.g., [36,67]), assessing acceptability (e.g., [3]), considering timeframes or critical windows [3], and integrating political considerations (e.g., [13,20]) to offer potential trade-off guidance.

Additionally, societal and cultural imperatives are incorporated into the risk maps to ensure that decision-making gains social acceptance and maintains a social license to operate (e.g., [68]). Evaluating trade-offs become a crucial aspect of risk management, guiding decisions on the best course of action and determining the appropriate timing for implementation.

2.2.6. Step 6: Implement, monitor, and adapt

Based upon the previous 5 steps, risk management decisions are implemented, with specific monitoring designs (if needed). When actions are required or decided upon, the monitoring designs can be implemented with action plans for high-risk NIMS. Action plans aim to inform the framework as to when and where objectives have been met (or progress towards meeting objectives), within agreed timeframes. Outcomes are reviewed at practical timeframes to capture short-, medium- and long-term planning. If the outcomes show that actions need to be modified or adapted, then adaption is made, implemented, monitored, recorded and reporting is updated (e.g., [40]).

2.2.7. Overarching all Steps: Communicate the decisions and risks

Risk communication is multi-faceted and requires an ability to anticipate issues and respond to incursions effectively. In these situations, communication must align with emergency risk communication principles. It is crucial to understand the emotions and actions of citizens during decision points 3 and 4, as well as providing credible and trustworthy information (decision point 3) to the public.

To ensure effective risk communication, biosecurity agencies and their partners should have well-developed decision processes and action plans ready to implement during decision points 1–4.

There are two fundamental mechanisms that can greatly contribute to risk communication in such scenarios. First, providing clarity regarding the nature of the hazard, such as a specific NIMS, helps individuals to better comprehend the situation. Second, addressing specific citizen concerns related to the hazard, which can be achieved through message mapping (e.g., [18]), which helps to alleviate fears and fosters trust within the community. By utilising these approaches, effective risk communication can play a significant role in managing biosecurity threats.

Fig. 3 illustrates an example marine biosecurity message map, which serves as a model for conveying essential information (in this instance related to a simulated *Sabella spallanzanii* incursion). The purpose of a risk communication plan that uses message maps is to offer clarity in the event of a marine biosecurity incursion, aiming to ensure that all individuals comprehend the biosecurity management messages, particularly for scenarios involving catastrophic risks or those perceived to have a significant impact on citizens. In Fig. 3, we have used the simulated incursion of a *S. spallanzanii* into Auckland Harbour, NZ. There is an overarching question or concern (e.g., why care or respond to a *S. spallanzanii* incursion), followed by the three key messages, with supporting information.

By employing an audience-centred approach, the messages are tailored to cater specifically to the intended audience, ensuring a clear understanding of the situation and the potential spread of the incursion. This approach also prevents the audience from being overwhelmed with unnecessary details. An example of such an audience-centred approach can be seen in Fig. 4.

In Fig. 4, the outer ring represents individuals in the audience who are not affected by the risk or the communication about the risk. Moving inwards, we encounter the latent public, who are affected by the risk but are unaware of it. Next, there is the aware public comprising individuals who are both affected by the risk and are aware of it. Finally, at the core, we find the active public, which consists of individuals who are not only affected by the risk but are also organised and ready to take action in response to it [48]. The information that is conveyed to the relevant parties increases in detail and complexity as we move from the outer ring to the inner ring.

When communicating decisions based upon a species incursion and its associated risk profile, it is crucial to recognise and address the presence of uncertainties within a broader societal context. In certain cases, such as when dealing with a new species arriving in New Zealand without any previous invasive history, the risks and ultimate consequences may not be well-defined. In such situations, the level of uncertainty depends on how we respond to the incursion at hand. Nevertheless, amidst this uncertainty, it is essential to grasp the societal concerns and perspectives to effectively communicate the risks and decisions made. Facilitating an open dialogue with citizens concerning their concerns will prove invaluable in mitigating the potential amplification of risks. This process of engagement should explicitly acknowledge and delve into the uncertainties, exploring the implications they might have on the overall situation.

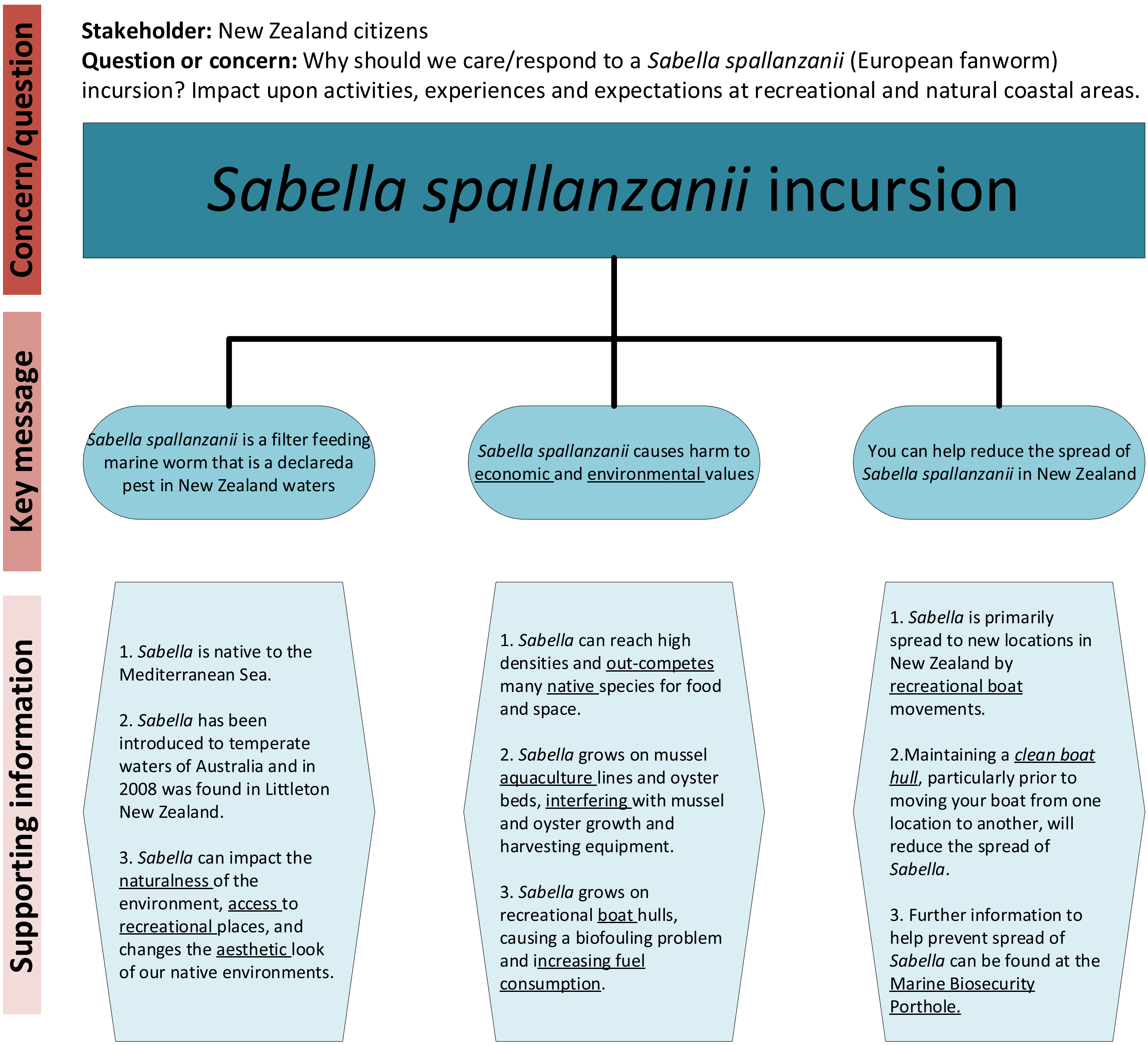

Fig. 3. Marine biosecurity message map example, for a simulated incursion of *Sabella spallanzanii* into Auckland Harbour, New Zealand. The message map (e.g., [18]) uses underlined font to highlight keywords.

3. Discussion and conclusions

Rapid decision-making necessitates preparedness with clearly defined and transparent principles. Preparedness includes understanding the relevant environmental, economic, social, and cultural values in a spatially explicit fashion. The principles must integrate the multiple dimensions of values alongside societal concerns, through open and transparent risk communication. We have illustrated a framework that transforms the current risk assessment paradigm to enable the incorporation of these critical elements iteratively.

When utilised, the holistic marine biosecurity risk framework (Fig. 1) expands the range of information accessible to environmental managers and policy makers for critical decisions. Crucially, it ensures that all relevant parties voices are heard. We highlighted a critical challenge in identifying and consulting with relevant stakeholders as a critical step in post-incursion response can readily be planned in advance for likely incursion locations. Specifically, gathering an understanding of public perception of values, and generic attitudes, norms and beliefs around intervention options can enhance public trust and pre-consultation can reasonably be used to enhance rapid decision-making.

The risk communication tools focus on delivering specific, useful facts without being overwhelming (Fig. 3), and we recommend tailoring this information based upon the audience (Fig. 4). This transparent approach enhances efficiencies and fosters community trust by engaging relevant parties at each step. By integrating community input into the biosecurity process, we move closer to reconciling differences between expert and community values and perceptions (e.g., [44]).

A distinctive feature of this framework is its flexibility regarding specific risk analysis tools, although we demonstrate typical risk matrices we commonly use. By not prescribing particular tools the framework enables users to employ their preferred risk analysis methods. Similarly, we acknowledge that data availability varies across species and regions (e.g., [13]). The framework facilitates a robust risk process using the best available information, ensuring consistency, and providing strong evidence to support national positions in World Trade Organisation challenges if necessary (e.g., [7]).

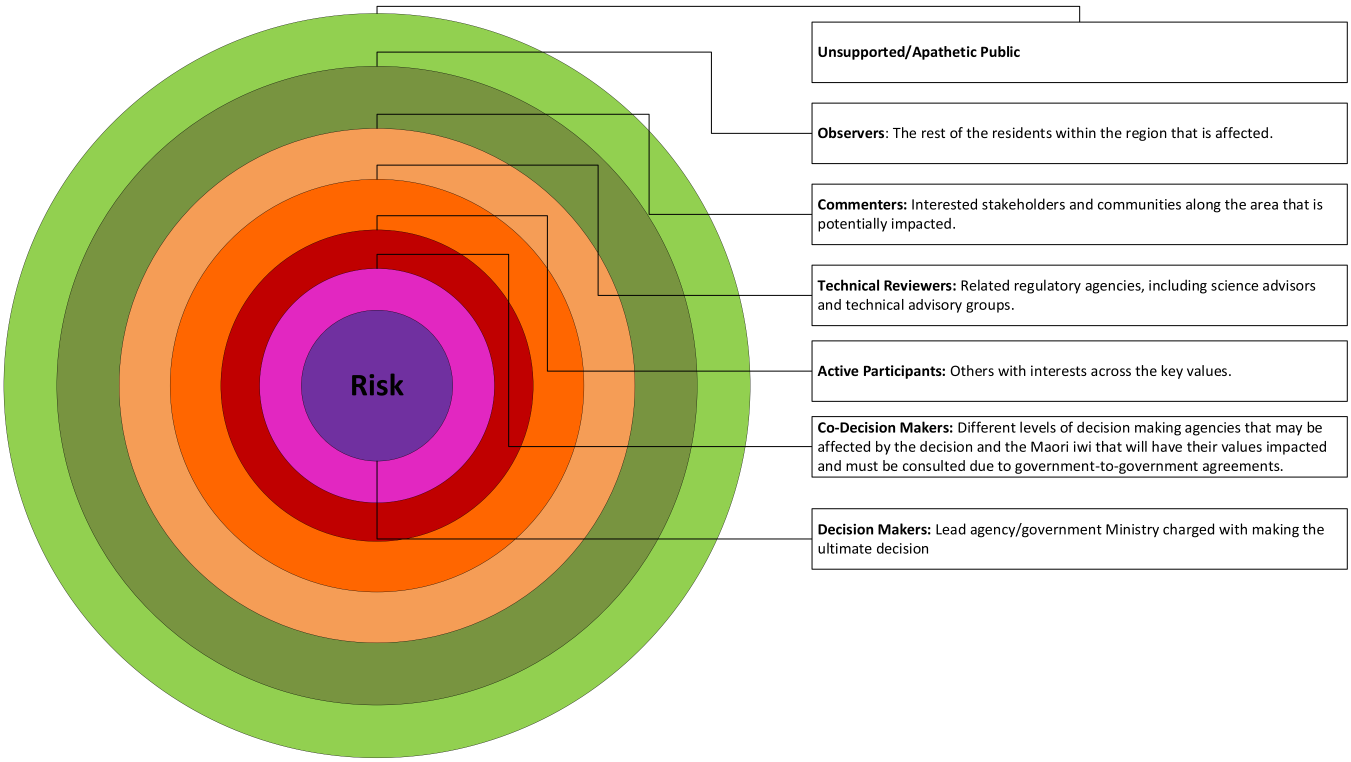

Fig. 4. Audience-centred communications plan for marine biosecurity, focussed on a simulated *Sabella spallanzanii* incursion to illustrate the plan. Moving inwards along the rings increases the depth of information released. If a participant is interested in more information, they may join the audience in the next inward ring. Those closest to the centre want to be more involved in decision making.

In conclusion, the framework's strength lies in its sequence of steps for handling incursions both proactively and reactively. A biosecurity framework that provides a roadmap for collecting information proactively, with proactive and reactive decisions points does not currently exist in marine biosecurity. Implementation of each step will depend on the legislation, regulations, and risk tolerance in the relevant geopolitical contexts. The utility of this approach is that it accommodates both complex and minimal data sets, offering a consistent methodology that considers all values (ecological, economic, social, and cultural), includes all relevant parties, and communicates risk throughout the process. Regardless of regional variations in risk analysis approaches, the framework remains neutral regarding the specific methods employed at each step. This neutrality provides a clear roadmap for conducting and preparing a holistic marine biosecurity risk process, making the framework applicable to any country, and adaptable to various hazards and threats beyond biosecurity.

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CRediT authorship contribution statement

Marnie L Campbell: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Chad L Hewitt:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors declare that generative AI and AI-assisted technologies were not used in the writing process.

Conflict of Interest

The authors declare that we have no competing interests to declare.

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We thank the many people that have shared their opinions with us over the years, with regards marine biosecurity risk models and systems. We created this framework to provide guidance to help resolve the issue of managing NIMS. We've both worked in research and policy settings, and we note that although risk models can be numerous, functional risk frameworks are often lacking or too niche in focus. Hopefully this framework will help address this gap. We note that a portion of our research did require ethics approval (University of Waikato, Faculty of Science and Engineering, Human Research Ethics Committee; application numbers FSEN-2015–8 and FSEN-2016–08), but what we have published here did not require ethics approval.

Author statements

MLC and CLH conceptualised the ideas. MLC developed the risk model and framework, with feedback from CLH. CLH and MLC were involved in funding acquisition. MLC wrote the original draft, with MLC and CLH both reviewing and editting.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2024.106511.

Data availability

No data was used for the research described in the article.

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