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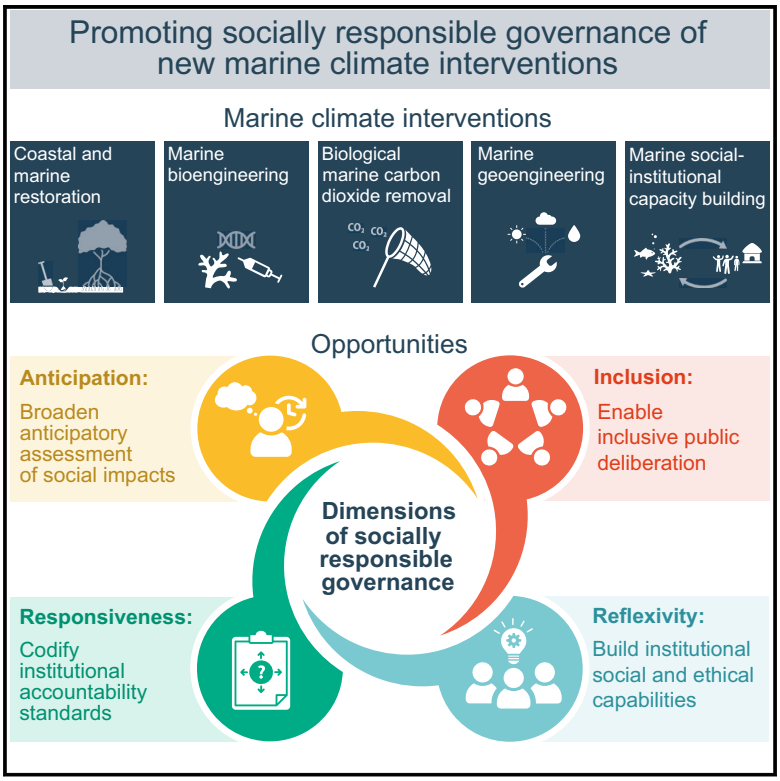
Promoting socially responsible governance of new marine climate intervention

Graphical abstract



Highlights

- Emerging marine climate interventions are popular but can bring social risks
- We assess the social responsibility of 76 marine climate interventions globally
- Foresight and management of social impacts are constrained by methods and expertise
- We recommend urgent governance reforms to ensure socially responsible ocean futures

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In brief

As climatic impacts in oceans intensify, novel marine climate interventions are increasingly popular. However, little is known about whether such interventions are socially responsible. Our analysis of 76 interventions shows limited anticipation of social impacts, restrictive public deliberation, and insufficient ethical and social competencies of intervening institutions. Governance reforms are urgently needed to improve intervention legitimacy, accountability, and sensitivity to societal implications. Such reforms can inspire better innovation by explicitly aiming for both socially responsible *and* ecologically sound ocean futures.

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Promoting socially responsible governance of new marine climate intervention

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SCIENCE FOR SOCIETY New interventions to address climate change in marine systems are rising in pace and scale, such as marine restoration, marine bioengineering, and biological marine carbon dioxide removal. These interventions hold the promise of reducing climate impacts and delivering global benefits. However, they also have the potential to reconfigure local marine systems, impacting ecosystem services, livelihoods, and use or access rights of ocean-dependent communities. Considering and managing such social impacts are key to socially responsible governance. Yet our analysis of 76 interventions being proposed, tested, and implemented globally shows that decisions about whether and how to intervene in marine systems often focus on scientific, economic, and ecological feasibility without fully anticipating or managing risks and benefits to people and societies. Opportunities to improve socially responsible governance of new marine climate interventions include (1) deliberate anticipation of possible social impacts, (2) inclusive public engagement in intervention deliberation, (3) ethically informed decisions, and (4) institutional codification of intervention best practices. Such reforms are critical to ensuring socially responsible *and* ecologically sustainable marine climate interventions.

SUMMARY

Novel climate interventions are proliferating and upscaling in marine systems. However, how social impacts are managed remains unclear. We combine a global survey of intervention actors, interviews with best-practice leaders, and policy analysis to assess whether and how social responsibility is considered when proposing, testing, and/or implementing 76 marine climate interventions worldwide. We find that technical feasibility trumps social considerations. Feasibility assessments predominantly rely on biophysical data (63%), with 54% either not using social data or relying on spatial marine use data as the only social data source. Where public deliberation opportunities are available (61%), most are via formal regulatory channels (54%), with only 15% offering more inclusive engagement. Best-practice leaders confirm low organizational competency around social impact. Social responsibility is rarely mandated by governments and instead relies on voluntary initiation by emerging best-practice leaders. Extension and codification of best practices are urgently required for socially responsible governance of new marine climate interventions.

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INTRODUCTION

The ocean is both a critical resource for climate mitigation and a critical arena for climate adaptation.[1,2] Global commitments to strengthen ocean-based climate action are therefore accelerating.[3–5] The Glasgow Climate Pact (2021) emphasizes this urgent need to scale up terrestrial and ocean-based action "to enhance adaptive capacity, strengthen resilience, and reduce vulnerability to climate change in line with the best available science." Correspondingly, a raft of new science-driven marine climate interventions are now being considered as scalable solutions to mitigate, or delay, climate impacts.[2,6,7] Examples of climate mitigation interventions include marine biological carbon dioxide removal, such as creation or restoration of carbon sinks from natural marine resources.[2,8] Climate adaptation interventions include assisted marine animal and plant migration, marine climate refuge protection, and solar-radiation control.[9–11] The testing, development, and implementation of such interventions are now occurring at multiple spatial and ecological scales across many marine systems.[2,7,12]

More than 3 billion people are also dependent on the health of these marine systems for their well-being.[13] While some marine climate interventions can address societal-scale challenges (i.e., reduced greenhouse gas emissions and improved biodiversity),[14] they do not all translate into direct social benefits (i.e., improved human well-being) at local scales.[15–17] In fact, some marine climate interventions can reconfigure local marine environments, with drastic implications for ecosystem services, rights, livelihoods, access, and freedom of ocean-dependent people and societies.[15–18] The costs of these interventions are often unevenly borne by the people most reliant on marine environments.[17–19] Indeed, focusing on the universal benefits of necessary climate action can overlook the uneven impacts these interventions have at local scales and, in fact, reinforce existing or produce new injustices.[20] Hence, adequate consideration and anticipation of the proximate (temporal and spatial) social risks and benefits of new climate interventions at all stages of development is not only an ethical imperative but also instrumental to addressing the social and economic dimensions of climate impacts. At a minimum, new marine climate interventions must help improve the social conditions of ocean-dependent people and societies.

The positive and negative social impacts of marine climate interventions can be moderated in the way interventions are governed across intervention stages and scales.[21–23] In other words, socially responsible marine futures require responsible governance and practice at all levels. At the global level, social responsibility is the province of international and intergovernmental bodies (i.e., the Intergovernmental Panel on Climate Change) and conventions governing the marine climate solution space (i.e., the United Nations Conventions on the Law of the Sea). At the national level, socially responsible governance is applied through federal decisions, regulations, and regulators (i.e., by national environmental protection legislation and authorities). At the local level, socially responsible governance can occur through policies and practices surrounding how marine climate interventions are developed and implemented (i.e., by research institutions, scientific agencies, practitioners, and funders). Urgency to delay climate impacts, however, can lead to the development of interventions with few agreed structures or rules to govern them.[24] For instance, marine geoengineering (i.e., seeding clouds to generate shading of coral reefs and ocean alkalinity enhancement) has stimulated concern about the relatively "ungoverned" nature of experimental research, including public liability in the event of negative social-ecological consequences.[21,23] Ungoverned interventions and their impacts can also be understood as a maladaptation, especially where the risk of intervention outweighs the benefit.[25,26] Maladaptation can occur as a result of technological lock-in and path dependency and crowd out alternative and socially innovative interventions.[27–29] This blend of both substantive risk (to people and societies) and governance risks (of ineffectiveness and maladaptation) highlights the need to ensure novel marine climate interventions actually progress socially responsible ocean futures.

Responsible innovation frameworks generally view responsibility as "taking care of the future through collective stewardship of science and innovation in the present."[28] However, while responsible innovation frameworks (e.g., Stilgoe et al.,[28] Owen et al.,[30] and Macnaghten[31]) offer conceptual guidance on the innovation phase of new climate interventions, they have not yet been applied to the governance of the deployment and upscaling of novel climate interventions, especially in marine social-ecological systems. Here, we adapt and extend Stilgoe et al.'s innovation framework[28] to develop and analyze four interconnected dimensions of governance: anticipation, inclusion, reflexivity, and responsiveness (Figure 1). Governance responsibility herein refers to ethical and moral obligations of governance actors (i.e., governments, scientists, practitioners, research institutions, and funders) to drive socially sustainable and just futures.[32] We purposively examine marine climate interventions considered novel (a category of analysis adapted from[1,2,33–37]). These interventions include those that are critiqued for their surrounding hype,[22] risk of over-promise,[23] and tendency to address symptoms of climate change rather than root causes.[22,29] Such interventions are generally regarded to pose the most risk to ocean-dependent peoples, communities, and societies because they are often pursued through an emergency framing,[24] which introduces pressure to forego social safeguards that force risk trade-offs upon communities because of the size and perceived urgency of the climate "threat."[21,23] As such, the rapid emergence of these novel interventions has exposed unclear and fragile governance arrangements.[9] This uncertainty is compounded by increasing investment in interventions by diverse funders,[38] such as impact-driven ocean philanthropists,[39] who are now playing de facto governance roles with few transparency or accountability mechanisms.[40,41]

To explore how distal and proximate social impacts are governed in the development of these new marine climate interventions, we (1) survey key actors (n = 243) engaged in interventions being proposed, tested, or implemented to boost the resilience of marine systems to global heating in both tropical and cold-water systems; (2) interview key intervention leaders nominated by survey respondents for emerging best practices in Australia, mainland US, Hawaii, American Samoa, and Indonesia

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Figure 1. Socially responsible governance of new marine climate interventions involves being forward-thinking, inclusive, self-reflective, and responsive

The concept of governance responsibility is extended from Stilgoe et al.[28] to specifically examine socially responsible governance of novel marine climate intervention in the deployment and upscaling phases.

(*n* = 7); and (3) review regulations and guidelines influencing selected interventions, including those nominated as influential by emerging best-practice leaders (*n* = 10). Our purpose is not to critique or evaluate the technical or ecological viability of new marine climate interventions themselves (for that see Hoegh-Guldberg et al.[1] and Gruby et al.[42]), rather, we probe the extent to which the governance of these new interventions accounts for and manages societal impacts and engagement. We aim to promote more socially responsible governance of new marine climate interventions as they are rapidly developed and upscaled.

Methods summary

To examine socially responsible governance of marine climate interventions, we extended the methodological heuristic for responsible innovation developed by Stilgoe et al.[28] to the governance domain (see methods). We used a mixed-methods approach to analyze four dimensions of socially responsible governance (Figure 1), choosing different methods to suit the availability of data and the foci of our examination. An anonymous global online survey (*n* = 243) was first undertaken to gather field-wide insights into the "anticipation" and "inclusion" dimensions of socially responsible governance. To gain organization-specific insights into the "reflexivity" and "responsiveness" dimensions, we asked survey respondents to nominate organizations they considered as best-practice leaders (see Table S1). Key informant interviews with senior managers (*n* = 7) from the three organizations most frequently nominated were conducted and combined with a review of regulatory and organizational documents nominated by those informants (*n* = 10). This combination of field-wide and organizationally in-depth data enabled applied insights into both the operationalization of socially responsible governance globally and the internal structures, processes, and capacities among leading organizations charged with designing and implementing interventions in a rapidly emerging field. We aggregate these data because, in many cases, the governance lessons are generalizable across multiple interventions, particularly in regions where policymakers are grappling with multiple interventions within the same ecosystem (for intervention-level analysis of these data, see Ogier et al.[37]).

RESULTS

Types and distribution of new marine climate interventions and best practices

The 243 survey respondents identified 76 unique marine climate interventions they were familiar with and answered survey questions based on the single intervention with which they were most familiar. The 76 interventions formed five separate intervention categories based on the interventions' objectives: coastal and marine restoration, marine bioengineering, biological marine carbon dioxide removal, marine geoengineering, and marine social-institutional capacity building (Figure 2) (see Table S2 for a comprehensive list). These interventions were distributed across nine geographic regions: Australia and New Zealand (temperate) (*n* = 39), North Pacific (*n* = 37), Australia (tropical) (*n* = 34), Caribbean (*n* = 22), North Atlantic (*n* = 19), Indian Ocean (*n* = 9), Mediterranean (*n* = 8), South Pacific (*n* = 4), and South Atlantic (*n* = 3). A further 12 were described as "global," and 56 had an unspecified geography. Of the interventions, 14% (*n* = 33) were at concept stage, 39% (*n* = 95) at pilot stage, 35% (*n* = 86) at implementation stage, and for 12% (*n* = 29) the stage was unspecified. Survey respondents also identified 67 organizations regarded as intervention best-practice leaders in different parts of the world (see Table S1). The three most cited best-practice leaders included a scientific agency, a research consortium, and an international non-governmental organization (INGO), who collectively operated across Australia, mainland US, Hawaii, American Samoa, and Indonesia (see methods for more detail). These best-practice leaders were interviewed and nominated and discussed 10 influential regulations and guidelines key to best practice (see Table S3).

Anticipation of social impacts

Anticipation is critical to ensuring socially responsible governance of marine interventions because it enables potential social impacts to be identified and appraised to inform

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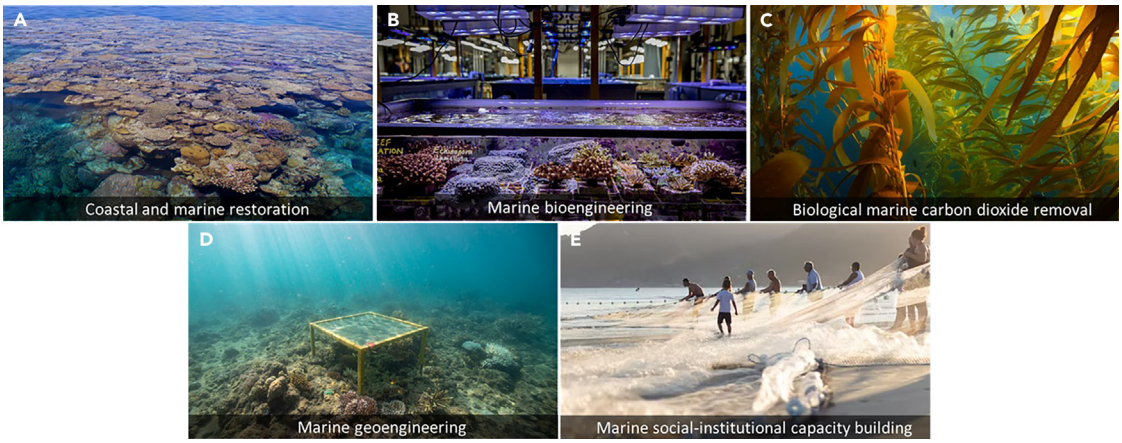

Figure 2. Marine climate interventions reported by survey respondents (*n* = 243)

Interventions included (A) coastal and marine restoration: catchment habitat restoration, natural stabilization of reefs and coasts, regrowing targeted coastal, and underwater species (*n* = 106); (B) marine bioengineering: artificial habitat manipulation, assisted evolution, assisted migration and colonization, controlling climate exacerbated destructive species (*n* = 95); (C) biological marine carbon dioxide removal: aquaculture for carbon sequestration (*n* = 22); (D) marine geoengineering: artificial upwelling and downwelling, ocean alkalinity enhancement, ocean fertilization, shading and cooling water and habitats (*n* = 11); and (E) marine social-institutional capacity building: anticipatory marine climate science, climate adaptive aquaculture management, climate adaptive fisheries management, climate resilient marine protected area management, coastal adaptation community planning (*n* = 9). Image sources: Australian Institute of Marine Science 1996 (CC-BY) (A, B, and D); Unsplash (CC-0) (C and E).

decision-making (Figure 1). We first examined anticipation in terms of the data types and sources used to determine the social feasibility of interventions, and second, the types of possible social impacts (risks, harms, and benefits) that were anticipated and measured.

Data types most frequently used to assess the feasibility of interventions included biophysical (63%), oceanographic or hydrological (52%), and spatial marine use (52%) data (Figure 3). The collection of spatial marine use data suggests there was some attention to human uses and activities in at least half of all feasibility assessments. Yet only some respondents (44% of total) considered spatial marine use data with at least one other social data type: 29% also considered financial or economic data, 28% cultural or social values data, and 26% traditional ecological use data. Over half of all respondents (54%) reported they either did not use social data (22%) or spatial marine use data were the only social data type used (33%). These results suggest a large proportion of current intervention feasibility assessments are unlikely to indicate how new marine climate interventions may impact the multiple dimensions of human well-being (i.e., social, cultural, and economic). Indeed, a respondent confirmed that "There is an awareness that all these data types [biophysical *and* social] are necessary[,] but only oceanographic/physical/biological/cost information has been incorporated at this time" (ocean alkalinity enhancement). This acknowledgment was shared by another respondent who suggested that "social, cultural, and economic feasibility do not seem to be on the radar currently" (assisted evolution of marine species). In reference to artificial habitat manipulation, a further respondent declared that no social data collection was required because "increased fish availability is of benefit to local fishers," while other respondents perceived social considerations to be unnecessary, especially in early development phases.

Our interviews with informants from best-practice leader organizations confirmed persistent difficulties in using social data to inform intervention feasibility. Referring to feasibility modeling for coral reef restoration, one informant stated that "social dimensions are really challenging [to account for].... Engineering using mathematical equations shows tangible ecological changes and then provides direction on how to develop solutions for these but not solutions for Traditional Owners, communities, and societies" (R5). Another informant reported the following: "Our Modelling and Decisions Support sub-program looks at costs and benefits of different interventions.… It's relatively easy to model ecological and biological outcomes, but the social and economic is much more difficult" (R2).

The survey also revealed the most common data *sources* guiding feasibility assessments were scientific literature and expert opinion (70% of respondents), trials and pilots (68% of respondents), and scientific monitoring (61% of respondents) (Figure 4). More than two-thirds of respondents (68%) reported they did not use public consultation as a data source for feasibility assessments. Of the respondents who reportedly undertook public consultation (32%), less than half specified that deliberation included Traditional Owners (TOs) or First Nation peoples (just 16% of total survey respondents).

The second aspect of anticipation we explored was the type of possible social impacts (risks, harms, and benefits) that were anticipated and measured to inform decision-making. Of the total survey respondents, 124 (51%) reported consideration of social impacts. For these 124 respondents, impact considerations predominantly pertained to local ecosystem services (80%), local communities (73%), local economies (54%), and TOs and First Nations peoples (34%) (see Figure S1). Qualitative open-ended survey responses referring to all five categories of intervention indicated that when social impacts were considered,

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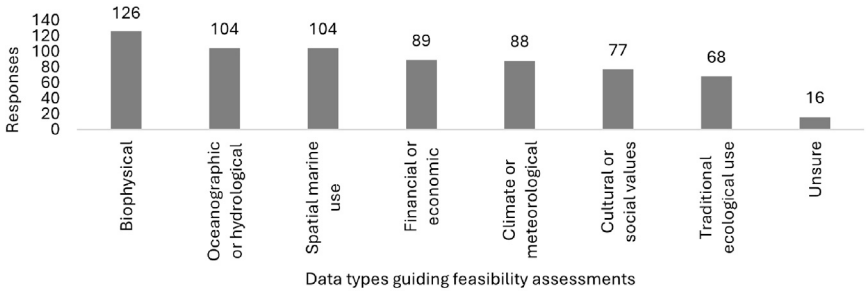

Figure 3. Data types reported as guiding feasibility assessments of marine climate interventions

Number above columns = number of responses, and selection of multiple responses was permitted (total respondents, *n* = 199).

they were "not done at scale," the depth was "very limited," often in the form of "informal feedback" from "very narrow audiences," and that "generally impacts that are considered are more on the biological systems." Referring to artificial habitat manipulation in particular, a survey respondent stated that impact assessment was biased toward positive impacts: "Impacts are almost always considered to be positive. Social impacts focus on selling people a magic cure for the problems of climate change and reef decline." The types of data used in these assessments were also critiqued by another survey respondent who called for "much greater scrutiny around risk-reward value and public good" (assisted evolution of marine species).

The in-depth interviews confirmed that emerging best-practice leaders were invested in understanding potential future social impacts. One best-practice leader organization was spearheading interventions that were intended to be responsive to local priorities, future needs, and relative disadvantage through community co-designed and co-led restoration projects (R3, R5). Other leaders emphasized biocultural risk mitigation, which was assessed using community consultation methods (surveys and community panels) and involved partnering with Indigenous communities to mitigate such risks (R1, R2, R6, and R7). Another informant discussed their efforts to model possible social futures for a changing coral reef ecosystem: "We need to grapple with the reef being different … to decide the best compromise for people and ecology.... We can generate thousands of possible futures, but we need to understand this for different user groups [which is difficult] because we can't do everything.... We've done the economic analyses for Traditional Owners and how [they] can be a part of championing or leading the job opportunities. [Our] interventions are intended to create industries for people [and] job creation. [There are] some risks we account for, for example, some people might lose their jobs, like tourism" (R4). Despite these examples, all informants from the three best-practice leader organizations reported that anticipation of social impacts did not always feature as a mainstream consideration within internal intervention feasibility assessments, nor by regulators responsible for permitting and permissions. Furthermore, while some direct social co-benefits were being considered by best-practice leaders, many of these were limited to economic opportunities or minimization of biocultural risk with little acknowledgment of the broader ambitions (e.g., tenure and sovereignty goals) that many communities hold.

Inclusion of the public and stakeholders in deliberation

Inclusion is a second key dimension of socially responsible intervention governance because it enables critical public and stakeholder deliberation (Figure 1). In exploring the type and accessibility of public and stakeholder engagement, we found 61% of survey respondents (*n* = 155) reported opportunities were available to the public to deliberate or dispute interventions, whereas 28% of respondents reported there were no deliberation opportunities (10% were unsure). For the opportunities that were described, we grouped these into six deliberation types and then ranked them according to their level of inclusivity (Table 1). Deliberation opportunities were predominantly restricted to one of these six types, principally occurring through formal or regulatory processes set by federal agencies (i.e., The Environmental Protection Authority in the US or the Great Barrier Reef Marine Park Authority in Australia) (54%). Only 15% of deliberation involved active inclusion, regarded as the highest opportunity for meaningful engagement. We found only seven cases with multiple types of deliberation opportunities. A notable example

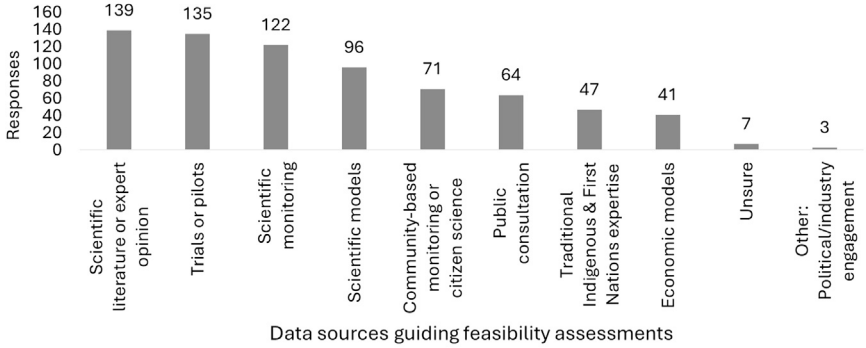

Figure 4. Data sources reported as guiding feasibility assessments of marine climate interventions

Number above columns = number of responses, and multiple responses were permitted (total respondents, *n* = 199).

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Table 1. Range and types of deliberation over new marine climate interventions reported by respondents

Deliberation type	Description	Examples of responses to open-ended survey question "Are there ways for members of the public to deliberate or dispute (intervention of focus)?"
Active (15%)	deliberation includes opportunities for intervention co-production or co-design; participation is inclusive of diverse perspectives, including those of scientific experts, industry experts (i.e., tourism), expert knowledge groups (i.e., fishers, local fishery councils, and veterinarians), and community representatives; public outreach is actively pursued, including via door-to-door communication, workshops, and community meetings	• "Public outreach sessions held in communities advertised by door-to-door communication" (regrowing targeted coastal species) • "[We] co-design [interventions] with all stakeholders, so they can have their input from the beginning of the project" (regrowing targeted coastal species) • "Deliberation occurs] during community meetings. Locals are the ones leading the effort" (regrowing targeted underwater species) • "Different presentations have been done to the different stakeholders (professional fishermen [sic] with representatives involved in the project, administrative committee with representative[s] of recreational fishing, veterinary services, etc.)" (regrowing targeted coastal species)
Proceduralized (54%)	deliberation is permitted via pre-existing formal and regulatory processes or via mechanisms set by governmental or regulatory bodies (i.e., within permitting systems and development applications); formal proceedings may include public hearings and exhibitions	• "During permitting process, there is stakeholder consultation. The public can attend to deliberate or dispute" (artificial habitat manipulation) • "If it's a development application, they [members of the public] do get notified of intent through…a statement of environmental affects [sic]. [Deliberation is either] through public comments or direct engagement with our organization or the departments issuing approval" (natural stabilization of reefs and coasts)
Restrictive or purposive (7%)	deliberation opportunities are only accessible to certain groups (i.e., scientists at scientific conferences) or where a specific group is contacted directly for consultation	• "There are scientific conferences [that offer opportunities for deliberation]" (ocean fertilization) • "[Deliberation occurs] through scientific publications" (aquaculture for carbon sequestration) • "[Deliberation occurs] when scientists contact users" (artificial habitat manipulation)
Reactive (11%)	deliberation is up to the public to instigate; examples may include public demonstrations, social media engagement, or through reactive processes including council grievance mechanisms, letter writing, or chance encounters	• "[Deliberation occurs through] public opposition such as demonstrations before research ship departure" (ocean fertilization) • "Many projects have social media where they could receive feedback" (artificial habitat manipulation) • "In any democracy, the public can always interact with both the government and it's [sic] agencies as well as with elected representatives" (natural stabilization of reefs and coasts)
Intermittent or undefined (11%)	opportunities for deliberation are unclear and are intermittent, and inconsistently dealt with or responded to in an *ad hoc* manner	• "Agencies would respond *ad hoc* to concerns but redress is on an as need basis" (regrowing targeted coastal species) • "not in a well-organized way outside of the uncontrolled forum of the internet and social media" (artificial habitat restoration)
Exclusive and/or inaccessible (2%)	deliberation is restricted to narrow opportunity windows or promoted by powerful actors with little opportunity to change the trajectory of intervention pathways	• "Communities are usually consulted or informed well after plans have already moved ahead or received investment" (natural stabilization of reefs and coasts) • "Often [the intervention] is seen as coming from government, therefore people feel helpless to dispute it" (artificial habitat manipulation)

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was an artificial habitat restoration intervention, which included "proceduralized deliberation" via "public advertising of habitat restoration proposals through government processes," as well as "active inclusion" via regular community consultation processes, which was perceived as "important for successful project development and site selection."

In reflecting on the quality of dialogue during deliberations, survey respondents indicated missed opportunities for more active and inclusive deliberation, including the need for "greater engagement with Traditional or Indigenous (peoples) and local communities" (regrowing targeted underwater species). Other respondents reflected on the need for deliberation as part of "appropriate due diligence and full, prior, and informed consent procedures. In reality, [this depth of deliberation is] probably unlikely especially for experimental sites" (regrowing targeted underwater species). Other respondents were more skeptical of the objectives of community consultation, suggesting this form of deliberation was used to gain social acceptance and merely "offers false hope and detracts from real threats, [specifically] climate change" (regrowing targeted underwater species).

All key informants agreed public buy-in (also known as "social license to operate") for interventions was an important component of social responsibility. However, the purposes of public engagement differed among informants. For one informant, stakeholder engagement was primarily sought to overcome hurdles in intervention development, "Most of our social engagement is to achieve an outcome. If we hit a roadblock, we engage socially to understand how we deal with it" (R1). Another informant reported public engagement was focused on understanding public sentiment to assist narrowing intervention selection: "Some interventions are quite radical, so social license is important, asking people how they feel about it to see if they are onboard.… But it should be more than that. If we can show economic benefit [of these interventions] strategically, it helps the intervention to make sense" (R4). One informant emphasized "free, prior, and informed consent" when working with TOs for site selection (R7), with others promising co-design with Indigenous and TOs in implementation phases (R2, R4, R6). Participatory approaches were reportedly utilized by one best-practice leader organization: "But it's for more than buy-in; it's a way to ensure diverse thought and knowledge, to ensure we are responsive to local priorities and needs.... We consider these co-created projects enabling [local people] access to decision-making spaces … and transitioning [interventions] over to local leadership" (R3).

Reflexivity and competency of organizations to allocate social responsibility

Reflexivity, the third dimension of social responsibility, refers to how and to whom intervention organizations are allocating the moral labor of socially responsible decision-making (Figure 1). Moral labor refers to the duty that institutions have to be socially and ethically responsible in their processes, actions, and decisions when intervening in oceans and how that labor is distributed.[32,43] Survey respondents (n = 99) nominated 67 organizations as best-practice leaders (see Table S1). The three organizations most frequently nominated included a scientific agency, a research consortium, and an INGO (see methods). Key informant interviews with senior managers from these organizations revealed in-depth insights into how moral labor is distributed, as well as the internal social and ethical competency of these organizations. We found three types of distribution of moral labor among these emerging best-practice leaders (Table 2), with moral labor either (1) delegated and/or avoided whereby moral labor is transferred onto other parties, deferred through urgency narratives, and abrogated through lacking resources and expertise; (2) diffused and shared via institutional partnerships to access social science expertise and/or to prioritize local ownership and capacity transfer; or (3) deliberately and institutionally internalized, whereby organizations are actively building their internal social science and ethics competency, mainstreaming social justice principles, and accountability to a board and steering committee with diverse social membership. Despite evidence of all three distributions, we found dominance of the first type, i.e., a tendency for moral labor to be delegated or abrogated. Interview data suggested these three types of moral labor distribution were generating both challenges and opportunities (Table 2).

To explore internal social and ethical capacity and expertise, we asked leaders to describe their organizational processes and internal competencies to account for and improve social conditions. We found a divergence in described competencies. The INGO, for example, had a strategic focus on building their organizational social science capacity: "We work with socio-economists and economists for our distribution of benefits work. They provide analysis for government to support decisions using the science. We also engage gender experts. We have also recently employed a social safeguards expert. Our female CEO has been pushing hard for this. We also have an Indigenous engagement team" (R3). Despite these efforts, the INGO interviewee (R5) indicated they needed to undertake further work to ensure social benefits from interventions: "I think we could do a better job [of ensuring social benefits and] … be more thoughtful. There is more room for social sciences and to understand the different layers of social benefits. Most NGOs benefit from social scientists on staff, and they help prompt rigorous engagement."

The scientific agency, by contrast, had an internal Indigenous partnership team with a tiered strategy for engagement, and the research consortium had a dedicated sub-program focused on stakeholder and TO engagement led by three externally engaged social scientists. The scientific agency and research consortium both outsourced economists to play key roles in scenario modeling: "Economists are involved in our modeling for decision science, for example, capturing industry engagement on the reef" (R2). A research consortium interviewee (R2) also reported an outsourced social scientist "is working on the learning components that need to be developed to engage the correct people [in the future] to ensure there are pathways for engagement of younger TOs." The research consortium had also established an independent interdisciplinary expert group to consider the associated risks of marine interventions and provide guidance on risk assessment and management (R6 and R7). Despite this, R1 reflected on the lack of social scientists involved and expressed concerns about their organization's ability to adequately account for social risk. For example, both R1 and R4 from the scientific agency and research consortium reflected on issues

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Table 2. Challenges and opportunities in resolving the moral labor of intervention decision-making

Challenges		
Lack of moral and ethical resources and expertise	"[Social considerations are] not tracked for specific interventions. It's pretty hard to measure at that level.… It is a real weakness for us.… We do not know how to quantify these things [referring to social dimensions]. It takes us out of our comfort zone. We've engaged [external non-profit expert agency] to help us understand it, but we haven't acted on it." (R1) "It is important to recognize the need to have mechanisms to support socially enabling environments. We keep getting told we need to look at issues holistically and look at every single possible impact and benefit. But who has the time to do so? It takes time and commitment. Every person who works for INGOs says the same thing, they are overworked, under-resourced, and under-staffed." (R3)	outcome 1: moral labor is delegated or abrogated
"Urgency to act" narratives override moral and ethical deliberation	"We look at futures without intervention to show to [the regulator] and the government. We show that there is overall a downward trajectory for the [reef ecosystem]. This changes the risk lens. There is too much focus on managing risk of interventions and not the risks to the reefs." (R4) "The risks of the reef bleaching massively outweigh the risks of the interventions we are proposing.… In terms of societal understandings, people are conscious they don't want to make things worse [and may not accept proposed interventions], and we need to balance that risk for a particular point in time. But people do not understand the social risks [of not actioning interventions]." (R7)	
Easier to transfer social responsibility onto other parties	"I have one example [of an intervention] where we sought fish production increase. We then had to think about who gets the benefits of the stock increase. I work with national jurisdictions and hope they do it [benefit distribution] equitably and responsibly.… My job is to prove the ecology dimensions, it's then up to local structures to ensure [benefit] sharing." (R5) "Permitting and permissions by [the regulator] all refer to outstanding heritage values. That's the final standing, and this triggers questions about what's valuable [referring to the absence of regulatory oversight mechanisms for social risk and impact]." (R1)	
Opportunities		
Partnerships for social science expertise	"We also have a deliberative part in how [our intervention research program is] designed to ensure we get stakeholder perspectives on our risk management and governance. [Outsourced social scientists] do this through surveys, community panels, and projects with Traditional Owners where we assess biocultural risk.... This ensures their interests are adequately considered." (R6)	outcome 2: moral labor is shared and diffused
Partnerships for capacity building, knowledge sharing, and local ownership	"Best practice is science and learning exchange between regions, mainly through partnerships.... [Referring to a network of restoration partners globally] our focus here is on capacity building and knowledge sharing." (R3) "We need patience to work with completely diametrically opposed parties.... This can take up to two years. It is faster when regulators are partners, for example, a state environment department or a national government. Nobody's big enough to do this on their own." (R5)	
Organizational structures, principles, and processes for equity, consent, ethics, and good governance	"A key driver of this [employing social scientists and equity-focused personnel] is when we receive grants to invest in [human resourcing within] our organization. We have been able to establish a GEDI [gender equity, diversity, and inclusion] team to bring into existing projects and build the capacity of our staff.... When funders support … staffing [in social sciences], it is a game changer." (R3) "At the project level we ensure free, prior, and informed consent [FPIC].… Certain methodologies require ethics approval, so our ethical reflection occurs at multiple levels." (R3) "We are guided by independent members with 70 people on the board and on the steering committee … [including] Traditional Owners, members of the public, the Department of Climate Change, and so on." (R7)	outcome 3: moral labor is internalized

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of social inequity in the implementation of interventions, particularly regarding site selection when there is traditional ownership: "We need agreement about who Traditional Owners are.… For instance, how to approach saving a reef in one community and not another? How do you make that decision?" (R1). In contemplating these challenges, R4 also questioned the overarching benefits the interventions were realistically likely to bring, "I helped conceive [interventions], but I am currently asking, 'is this really going to work?' My concern is that the money that's gone into[it] is not doing enough." R1 suggested the interventions the scientific agency had developed were likely already bringing social benefits but explained their organization lacked the capability to demonstrate such benefits, despite knowing they "should."

Responsiveness of social accountability mechanisms

Responsiveness is the fourth key dimension of socially responsible governance and refers to the presence and extent of formal oversight and guidance to assess and manage the social impacts of new marine climate interventions (Figure 1). Our results revealed formal mechanisms were still emerging, with only a small sample of instruments (n = 10) reported to be drawn upon when considering social and ethical dimensions of interventions. Influential regulations and guidelines nominated and discussed by best-practice leaders included federal regulator intervention policy, risk and governance assessments (n = 4), organizational partnership and engagement plans (n = 4), and intervention implementation guidelines (n = 2) (see Table S3 for full list).

Nominated federal instruments (i.e., social impact and risk assessment scales, social value assessments, and TO heritage assessment guidelines) predominantly counseled that interventions must "do no [social] harm" by "minimizing negative impacts … [upon] intrinsic, environmental, biocultural, social cultural, and economic values." Such guidance emphasized the need for intervention proponents to be "supporting and encouraging the consideration and involvement of Traditional Owners'." However, within these instruments, such outcomes were typically described as "secondary." For example, best-practice leaders stated that they adhered to global conventions such as the *London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972)* as well as national and state regulation of relevant sectors (i.e., fisheries, endangered species, and gene technology). However, all leaders emphasized the primary focus was on managing environmental rather than social damage and risk. Only one key informant acknowledged that "there are multiple regulators (and) multiple values; social, economic, and TO heritage (are considered)."

Outside of these limited examples, leaders claimed that mechanisms for accountability were designed and developed voluntarily by their organizations, specifically for ethics, social risk, and impact assessments of interventions, as well as planning for responsible exits. This voluntary commitment to accountability was evidenced by one leader who explained "We have ethics processes that are not required and not imposed [by regulators], but we have chosen to adopt, so internally we also have a lot of oversight layers" (R6). Other accountability mechanisms related to public openness and transparency, "the idea is that anything we develop can be used and shared elsewhere through enabling public access and public intellectual property" (R6). Although not applied consistently across all marine interventions, other key informants described organizational mechanisms whereby embedded social protection instruments were used prior to and during intervention development (i.e., human rights guidance, guidance for Indigenous and community-led interventions, and protocols for ensuring accountability to Indigenous rights holders) (R1, R2, R3, R6, and R7). Another informant reported that "Part of our ethics process involves developing new protocols and practices, for example, if coral translocation occurs, what are the protocols to ensure Indigenous ownership is respected?" (R2). Informants also discussed mechanisms to ensure responsible exits in terms of intervention transfers or transitions to external parties (i.e., industry, communities, and government) (R4, R5, and R7). An interviewee from a research consortium reported they were actively considering safe and responsible transitions to industry that align with regulatory environments. Examples included turning intervention research and development into business opportunities for tourism and fisheries sectors, as well as TOs. Other informants focused on community-scale transitions, whereby their exit strategies sought to ensure ownership of interventions through community-led projects. An informant from the INGO explained "[We] push exit strategies, and are always looking at who can take over, and what that would look like.… We aim to work with local communities and hand over [projects] to tribes on a case-by-case basis" (R5).

DISCUSSION

We explored socially responsible governance of a diverse range of novel marine climate interventions by examining how social impacts are managed and accounted for and identifying "best-practice" examples from peer-nominated leaders in this rapidly emerging field. Our findings indicate that across the field, most marine climate interventions are developed, piloted, or implemented without adequate consideration of the methodologies, models, and engagement processes that anticipate and account for potential social benefits and harms. These findings are concerning given that 75% of new marine climate interventions described are already at either pilot or implementation stages. Fortunately, interviews with best-practice leaders reveal some consideration of social impacts and emerging efforts to build competencies and accountability to address the social and ethical implications of intervention (Figure 5). While beyond the scope of this dataset and analysis, we acknowledge that socially responsible governance may be applied in different ways among a broader suite of social, economic, and institutional marine climate interventions not represented in our sample. Building from examples revealed by our research, here we discuss four opportunities for the field to progress toward socially responsible governance of novel marine climate interventions.

Expand anticipatory measures to account for social risks, harms, and benefits

Novel and emerging marine climate interventions inevitably bring uncertainties, risks, and ethical concerns.[21,29] While the use of expanded anticipatory measures to predict social impacts is now being recommended to improve ocean policy and

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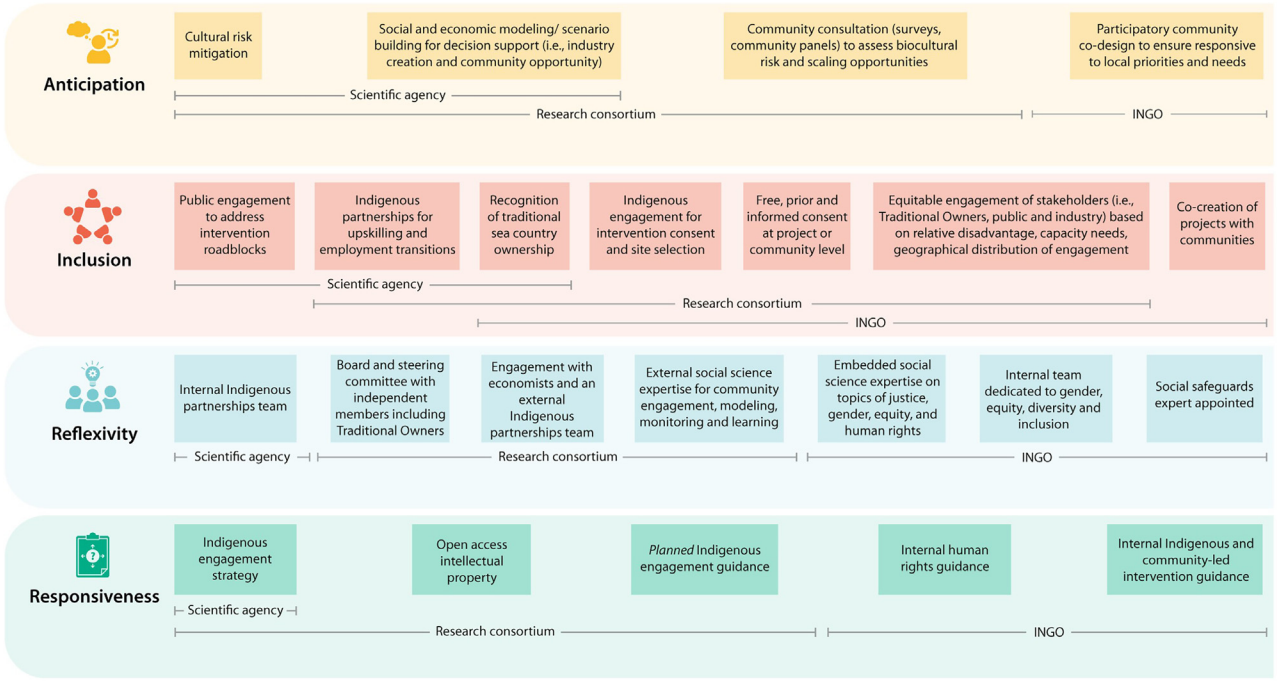

Figure 5. Socially responsible governance by best-practice leaders in marine climate intervention

management,[44–47] our results confirm that such measures are under-utilized in the more emergent and experimental interventions explored in this study. The generation of social data to anticipate potential social risks and benefits has two main benefits: (1) to avoid reproduction or amplification of existing inequalities and power imbalances, and (2) to find opportunities that drive more equitable and sustainable ocean futures.[48] To reach these two fundamentally critical goals, anticipatory measures must therefore be integrated from the outset in intervention research, design, and development processes to help articulate and maximize socially just outcomes.[30,44,49] Examples of such measures include hypothetical scenarios and future thinking, which are employed, for example, in the Future Seas 2030 transdisciplinary research initiative[16] and the Radical Ocean Futures art-science program.[46] Such approaches are focused on generating inclusive visions of ocean futures to reflect the values and needs of marginalized groups often excluded from decision-making forums.[45] A specific application of proactive anticipation of social impacts is also evident in some marine protected areas planning.[44,50] Here, qualitative methodologies such as place-based community visioning of possible futures, hypothetical scenario development, and storytelling can be employed with stakeholders to understand and construct plausible and desirable futures.[44] Such methodologies aim to capture diverse dimensions of well-being and dynamics that are too complex, localized, or uncertain to be captured by other (often quantitative) anticipatory measures.

Such anticipatory measures could be better utilized by research institutions, science and technology investors, ocean funders, and decision-makers in the challenging position of being forced to prioritize and approve multiple interventions proposed within the same system.[37] For example, there are a range of novel marine interventions being proposed, piloted, and deployed in the North Atlantic and tropical waters adjacent to Australia, presenting governance challenges for decision-makers who are potentially unprepared to prioritize interventions while managing their cumulative and synergistic impacts within certain marine regions.[37] In such cases, anticipatory measures would not only prompt ethical reflection on the ecological and social implications of novel marine climate interventions but also tackle fundamental justice questions related to distribution of interventions, outcomes, recognition of rights, and equity of process.[48,51,52] Specifically, anticipatory questions that capture justice dimensions of marine climate interventions should include "who may benefit or be harmed," "what social implications are being considered, modeled, and measured," and "whose visions of the future are being drawn upon?" Engagement with such questions should prompt more balanced consideration and collection of data needed to understand intervention implications for different social groups. At the very least, research institutions, investors, and decision-makers must begin to consider these questions in their own internal decision structures and feasibility assessments. Yet ultimately, to be effective, formal development and integration of multiple approaches, methods, and tools, as well as diverse participation and community engagement modes, are necessary to ensure inclusive visions of the future and planning for intervention trade-offs.[44] These future-oriented measures should not be seen as a restriction on innovation. In fact, these measures may also offer new inspiration and opportunities to expand the current marine climate intervention solution space and, simultaneously, drive more socially responsible outcomes.[53,54]

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Ensure inclusive public engagement for legitimacy and socially desirable outcomes

Our examination of public engagement opportunities indicates deliberation is typically limited to one means, predominately formalized deliberation required as part of a governmental or regulatory process. Only one best-practice leader, an INGO, reported actively offering public deliberation processes prior to intervention design (i.e., through co-produced projects to ensure responsiveness to local priorities and needs). These results raise concerns about when engagement is occurring, who is participating, and whose voices matter in the development of novel marine climate interventions. This was particularly apparent in cases where deliberation processes primarily sought "social buy-in" and public acceptance of interventions or where decision-making spaces were impenetrable to the public and diverse stakeholders. In the case of blue carbon restoration projects, for example, the global appetite for carbon mitigation "solutions" has, in many instances, led to the exclusion of local community representatives from high-level international decisions about these interventions.[1] Such decisions, while framed as providing global societal good, have denied access and eroded the rights of those most dependent on ocean and coastal resources,[55] with potentially drastic implications for food and nutrition security, livelihoods, and cultures.[17]

Inclusive deliberation is not only ethically responsible but can also foster marine stewardship, ocean literacy, and diverse societal gains.[56] In doing so, inclusive deliberation can improve the legitimacy of interventions and of their proponents.[28] Indeed, genuine deliberation processes guided by principles of procedural justice that center human agency, decision-making, and respect (see Ruano-Chamorro et al.[57]) are critical given the status of coastal communities and Indigenous peoples as rights holders, and in many cases, their experiences of disempowerment via externally led scientific, management, and conservation activities.[58,59] These processes are important for ensuring that local and traditional knowledge and rights are recognized and engaged with (if appropriate and not extractive). Indeed, more sophisticated forms of deliberation are crucial given the vast majority of (published) marine intervention science is conducted out of institutions in the Global North,[60,61] often resulting in marine management tools and approaches underpinned by Western norms.[15,62]

There is substantial opportunity for governments, non-profit organizations, ocean philanthropists, and research institutions to re-evaluate both the means and the goals of public engagement in the development and deployment of novel marine climate interventions (see Lawless et al.[36]). Genuine public deliberation of the design, direction, and delivery of novel marine climate interventions can provide critical opportunities for organizations to test the assumptions, ambitions, needs, and benefits of intervening.[28] Revisions would also require more stringent, inclusive, and regular public consultation as part of formal regulatory or permitting procedures for proponents seeking permission to conduct intervention research and deployment. Such revisions should improve engagement so that the voices and needs of society's most vulnerable or affected populations are meaningfully included[63] beyond simple regulatory adherence and social license to operate. Fostering opportunities for genuine input (rather than passive or consultative, see Arnstein[64]) ensures local actors are engaged on matters that may affect them at all stages of intervention development. Organizations such as the International Association for Public Participation offer targeted initiatives to advance community engagement globally and are guided by culturally adaptive standards of practice.[65] Engagement with such initiatives and standards would ensure marine climate intervention engagement processes are better able to center those most vulnerable to climate change in discussions, including enabling coastal communities and Indigenous peoples to determine the research and interventions undertaken in their territories.[59,66] The more familiar and embedded people are within science and intervention processes, the more likely they are to trust and support investments and maintain public support.[67] Likewise, disengagement between science and society can erode public trust in institutions and their research investments.[63,67]

Internalize and share moral labor and build social and ethical competencies within organizations

We find that delegation or abrogation of moral labor and lack of social and ethical competency are significant challenges for socially responsible governance of marine climate intervention. Our data suggest that moral labor, the duty that institutions have to be socially and ethically responsible in their processes, actions, and decisions,[32,43] is commonly being abrogated through claims about the "urgency to act." For example, the urgency to address climate threats has meant longer timeframes, additional expertise, and inclusion of diverse perspectives are less likely to be prioritized, and social considerations are at risk of being overlooked altogether.[21,23] We find such challenges are reinforced by limited organizational social and ethical expertise and/or views that social responsibility is labor to be handled by others (i.e., regulators, local governing agencies, or communities, rather than those designing, testing, and implementing interventions). Such findings raise questions about motives, potential social impacts, and ultimate accountability if something goes wrong.

Despite these challenges, we found some promising examples of deliberate and internalized moral labor among best-practice leaders. Common examples included internal human rights guidance, Indigenous engagement protocols, and dedicated human resourcing to account for social and ethical implications, and less commonly, shared responsibility through institutional partnerships. This sharing of responsibility is important because it can invite alternative values, visions of the future, and identification of potential social challenges.[30] Indeed, Choi-Fitzpatrick[68] argues that climate change and growing social inequity warrant disruption to existing thinking, "if we want to see new things, we need new perspectives, new frames of reference, and new epistemic communities." Responsibility that is shared between academic and non-academic actors, across diverse knowledge systems, including expertise that spans the social and natural sciences, can ensure that ethical, social, and cultural implications are adequately considered.[69–71] However, caution is needed to avoid another form of abrogation, where TOs, communities, social scientists, and ethicists become peripheral experts responsible for addressing negative social impacts after the scientific and innovation processes are

complete.[72] As such, a combination of internalized and shared moral labor may be warranted.

Our findings, similar to those of others,[32] indicate that leading governance bodies may not be playing their part in realizing and efficiently allocating the moral labor for socially responsible practice. In fact, organizations intervening in oceans (i.e., governments, scientific agencies, NGOs, funders, or multi-lateral agencies) rarely have, or invest in building, sufficient social engagement and social science capacity.[69] We found social and ethical competencies varied significantly between organizations and interviewees, meaning social responsibilities and implications of interventions were at risk of being considered in inconsistent, *ad hoc*, and uncoordinated ways. Here, there are both opportunities and responsibilities for marine-dependent peoples and the marine social sciences to play a larger role in resolving trade-offs, competing values, inequities, and conflicts that may currently hamper the reflexivity, inclusiveness, and transparency of these best practices (see Vadrot et al.[70]). This means TOs, community representatives, social scientists, and/or ethicists need to be embedded within organizations funding or intervening in oceans. Likewise, social scientists have a responsibility to be leading voices and play a greater role in shaping social responsibility requirements.[70]

Given the proliferation of novel marine climate interventions and the diversity of organizations emerging as leaders in this field, further research into the social and ethical responsibilities of individual actors and how this moral labor should be best assigned and enforced is crucial. Indeed, the UN Ocean Decade presents a major opportunity to develop greater clarity around responsible ocean-based climate action and strategic guidance on the implementation of key actions to reconcile divergent views of social responsibility and accountability. Clear responsibility requirements are particularly critical in the case of responsible exits, regarded as a ubiquitous but understudied problem,[73] and will be a necessary area of inquiry for the distribution of moral labor as new marine climate interventions spread. Established responsibility frameworks, such as the one we apply in this study, will be useful in developing this nuanced understanding.

Shift the focus of social accountability from "do no harm" to "do good"

Our results revealed that in the few cases where social considerations were made explicit in regulatory instruments, the prevailing focus was minimizing or mitigating social (often cultural) risks, signifying a do-no-harm approach to responsibility.[68,74] Do-no-harm approaches may be appealing as they do not require significant adjustment to intervention goals, design, or implementation. Mitigation of social risk becomes the maximum consideration of social accountability and is viewed as a secondary, supporting factor to the primary goal of achieving climate intervention ambitions. This approach to social accountability is likely the most palatable to intervention proponents who do not have the work history or expertise to adequately consider social implications. Indeed, do-no-harm approaches used in other marine contexts have been found to be instrumental to facilitating or accelerating technical or ecologically focused intervention goals.[75] However, such approaches rarely translate into direct social benefits (i.e., for human well-being) at local scales where marine reliance is high.[15,16,19]

Do good approaches, by contrast, focus on accountability for proximate societal benefits, whereby interventions must directly respond to the interests, needs, and values of societies and pay specific attention to recognitional and distributional justice (i.e., protection of rights and equitable distribution of benefits from interventions).[72] Marine climate interventions have the potential to better align with and extend existing climate and human development commitments that actively advance the status and well-being of rights holders and coastal communities.[55] For example, the United Nations Framework Convention on Climate Change (1992) calls for actions that support (and do not undermine) resource rights for local communities, Indigenous peoples, and other vulnerable groups. Sustainable Development Goal 14b commits to ensuring that access of small-scale fishers (the largest group of ocean users, more numerous than all other marine economic sectors combined[17]) to coasts and marine areas is protected, and by extension, that their access is not overtly reduced by any interventions. The Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries & Forests (2022) include many principles to ensure that local rights holders experience agency and opportunity in any actions that might impact upon their rightful lands, coasts, waterways, and associated resources.

Despite these diverse and high-profile examples of global human development commitments and guidance, evidence of outward adherence to such principles was not observed in our study. Instead, we found impetus for socially responsible interventions was voluntarily initiated by best-practice leader organizations. These organizations were all involved (to differing degrees) in the development of internal mechanisms and processes that helped account for and manage ethics, social impacts, and responsible exits (i.e., human rights guidance, Indigenous engagement protocols, and commercial upscaling and/or transfer strategies). While we found these internally developed guides and protocols demonstrate commitment to socially responsible practice, global scholarship indicates that these intentions do not (yet) translate to realized and perceived responsible actions. Instead, much resistance and concern are arising from the proliferation of marine interventions that are marginalizing parts of society from spaces and resources to the extent that tenure rights and human rights are abused.[55,76] As such, there is a pressing need to pair existing organizational-level efforts with established policy and legal instruments to which interventionists are socially obliged or legally required to adhere (i.e., those instruments described above). Introduction of additional financial measures may also demand organizations obtain ethical accreditation to access climate intervention funding, including national standards that set accountability and performance measures and interrogate donor-recipient incentives.[77] In fact, many civil society groups and social movements that represent coastal communities, small-scale fishers, and Indigenous peoples may well take the position that for marine climate interventions, and their governance, to be considered as "socially responsible," they must be in accordance with one or more of the aforementioned instruments and measures.

Conclusion

The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) is a once-in-a-lifetime opportunity to operationalize ocean science-based solutions to achieve the 17 Sustainable Development Goals. Socially responsible governance could ensure novel marine climate interventions help improve, rather than disrupt, the social conditions of ocean-dependent people and societies. Yet our global study revealed that attaining societal gains and avoiding societal risks is encumbered by the fact that social responsibility is considered narrowly, if at all. We find social responsibility to be viewed as a set of moral or ethical requirements intended to serve public acceptance of interventions and secure the investment needed to intervene at scale. At worst, we found that social responsibility was viewed as an unwelcome burden and constraining condition for interventions themselves. We argue that better processes to ensure social responsibility can be a source and springboard for enhancing innovation and the delivery of direct social benefits. Such processes must include increased sensitivity to societal risks and benefits; improved intervention legitimacy, transparency, and accountability; and stronger alignment with justice-oriented policy instruments to which interventionists are legally, financially, or socially obliged. These processes may also prompt new thinking on how to expand the current marine climate intervention solution space and subsequently drive more, not less, innovation toward socially responsible *and* ecologically sound ocean futures under climate change.

METHODS

Methodological approach

Findings are derived from the following primary and secondary data sources: global survey (n = 243 respondents), key informant interviews (n = 7 interviews), and policy analysis (n = 10 documents). To analyze the data, we extended the methodological heuristic for responsible innovation developed by Stilgoe et al.[28] to examine socially responsible governance of marine climate interventions (Table 3).

Global survey

Our anonymous online global survey was conducted between October 2022 and March 2023. We targeted researchers and practitioners engaged in interventions being proposed, tested, or implemented globally to boost the resilience of marine systems to global heating (total respondents n = 243). Survey recruitment was primed for respondents with knowledge of "new and emerging" marine interventions such as assisted evolution, cloud brightening, seaweed farming, coral propagation, and translocation. The limited scope of our study meant respondent recruitment was potentially exclusive of those with knowledge on a broader suite of social, economic, and institutional marine climate interventions. Despite our targeted study scope, 11% of interventions described by survey respondents also related more broadly to community-based management of reefs and marine resources (i.e., temporal and spatial closures) and physical and social marine infrastructure (i.e., fish aggregating devices and coastal community health services).

Our sampling strategy was designed to achieve saturation of the range of novel interventions currently being tested, implemented, or proposed globally. The size of the sample (n = 243) reflects the incipient status of marine interventions. Respondents included scientists or researchers (54%, n = 132), practitioners (agency employees, consultants, and not-for-profit representatives) (36%, n = 88), community representatives (TOs or First Nations persons, artists, journalists, activists, teachers, and students) (9%, n = 21), and marine intervention donors (1%, n = 2). The skew toward researchers is likely because 52% of interventions described by respondents were at either the conception or pilot stage, where researcher involvement is high. Ninety-two percent (n = 223) of respondents were familiar with a specific marine climate intervention for at least 1 year, with 44% (n = 107) reporting familiarity spanning 1–5 years; 27% (n = 65) spanning 5–10 years; 21% (n = 51) spanning 10 or more years; and 8% (n = 20) spanning less than 1 year. Informed consent to participate was obtained from respondents prior to commencing.

The survey instrument was created using Qualtrics. We structured the survey questions to elicit respondents' professional understanding of governance processes and data used to assess the feasibility, benefits, risk and impact, ethical implications, and social acceptability of marine interventions. Survey questions were predominately multiple-choice, with a small number of open-ended question formats. The survey sample design was non-statistical as the target group was a specialist group. Three rounds of recruitment were used. First, we employed purposive sampling via a web search of the programs, funding schemes, and listed activities of global organizations and networks associated with the proposal, testing, and/or implementation of marine interventions. Contact details of leading actors in these organizations and networks were obtained from publicly available publications and listings on public websites and were invited via email to participate. A second round of targeted recruitment invited participants within regions under-represented in the sample and associated with interventions or institution types not yet represented. To ensure global coverage, a third round of recruitment was undertaken via sharing the survey on social media platforms. The survey was produced in six languages, including English (EN) (83%, n = 203), Chinese (ZH-S) (5%, n = 12), Japanese (JA) (4%, n = 10), French (FR) (4%, n = 9), Spanish (ES-ES) (2%, n = 6), and Portuguese (PT) (2%, n = 5). Non-English text responses to open-ended questions were translated into English by a team of translators.

Quantitative analysis of survey data was undertaken via frequency distributional analysis of nominal responses. Because statistical or frequency distributional data may provide insight into what and how social dimensions are considered but tell us little about the depth, influence, and value associated with such consideration, we also included questions that invited open-ended responses. Within multiple-choice questions, respondents were also presented with opportunities to elaborate in an "other" category. These descriptive responses resulted in 323 sentiments (i.e., a view or opinion that was expressed in an open-ended response), which we analyzed using thematic analysis (see Braun and Clarke[78]). Examples of sentiments provided by respondents included views on the type of social impacts considered or the purposes of public engagement. We

Table 3. Methodological approach to assess socially responsible governance of new marine climate interventions

Dimensions of socially responsible governance	Foci of data collection	Research methods	Focus of analysis
Anticipation: extent possible social impacts are identified and appraised	intervention social feasibility data types and sources and social impact assessments	global survey; key informant interviews	foresight of social risks and benefits
Inclusion: inclusivity of public and stakeholder deliberation	type and accessibility of public and stakeholder engagement opportunities	global survey; key informant interviews	deliberation opportunities
Reflexivity: how responsibility is assigned; organizational competencies to interrogate social and ethical implications	identification of best practice; assignment of moral labor, ethics, and social science competency	global survey; key informant interviews	consideration for ethical and social dimensions
Responsiveness: presence and extent of oversight mechanisms account for and manage social implications	regulatory and organizational mechanisms to guide and manage social risks and benefits	key informant interviews; policy analysis	accountability for social implications

Dimensions are extended from Stilgoe et al.[28] to specifically examine socially responsible governance of interventions in the design, deployment, and upscaling phases.

used a combination of deductive and inductive coding to determine themes. Deductive coding involved assigning survey data to a pre-determined set of codes (or parent codes) based on survey questions. We then used inductive coding, where subthemes (or child codes) were determined based on emergent themes in survey data. Our thematic analysis was recorded and refined in a qualitative coding scheme (see Table S4), which we organized based on the four dimensions of socially responsible governance (see Figure 1). To ensure coding reliability (see Braun and Clarke[78]), two authors coded 100% of the survey data. The two authors then compared this coding to reduce bias and ensure agreement that parent and child codes were coherent with the dimensions of socially responsible governance outlined in Table 3. Although the exact proportion of comparative coding between authors was not quantified, several conflicts between codes were resolved during this process. The lead author then shared the coding scheme with all co-authors for feedback before finalizing.

Key informant interviews

As the reflexivity and responsiveness dimensions developed from the Stilgoe et al.[28] framework specifically refer to institutions, key informant interviews were deemed the most appropriate method to generate nuanced organizational understandings. We asked survey respondents to identify a "best-practice leader" associated with the marine climate intervention with which they were most familiar. The question was open to any type and area of practice. Sixty-seven different organizations and consortia were identified by respondents (n = 99), which we grouped into seven organization types (see Table S1). To understand the practices of the "best" in the field, we used stratified purposive and snowball sampling to identify knowledgeable and experienced candidates from the most cited organizations (n = 3) to conduct in-depth confidential key informant interviews (n = 7) (summarized in Table 4). Table 5 outlines the informants and their organizations (anonymized for human ethics purposes). Informants (n = 7) were either science managers (i.e., senior employees of a science organization with a publicly identified leadership role in design, experiments, and/or monitoring of interventions) or funding organization managers (i.e., senior employees of a non-profit organization with a publicly identified role in investment in programs for interventions in marine systems). Interview questions sought to understand aspects of best practice, leadership, organizational protocols, and codes of conduct to account for social dimensions, ethics and social science competency, partnerships, and moral division of labor. Interviews were conducted in person (n = 1) and online (n = 6). We recorded responses in writing and transcribed into Microsoft Excel. Our interview data were analyzed using thematic analysis following the same qualitative coding process described for our survey data (see Table 4). We undertook a further verification process where the best-practice data were summarized and presented back to informants to verify and provide feedback.

Policy analysis

We asked key informants to identify relevant regulations, organizational protocols, codes of conduct, or other guidance they

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Table 4. Types, interventions, and geography of best-practice leaders interviewed

Organization type	Interventions cited as best practice	Geography of interventions
Scientific agency: federally funded national marine science institute	marine bioengineering: artificial habitat manipulation (macroalgae removal and rubble stabilization) and assisted evolution (breeding climate resistant corals and coral reseeding)	Australia, American Samoa, Hawaii, and mainland US
Research consortium: multi-institutional research partnership	marine bioengineering: assisted migration of marine species and assisted evolution of marine species (selective breeding, microbiome manipulation, and hardening treatments) and coastal and marine restoration: regrowing targeted underwater species (coral aquaculture)	Australia
International non-governmental organization (INGO): non-profit entity operating internationally	marine bioengineering: artificial habitat restoration (oyster reefs and rubble stabilization) and coastal and marine restoration: natural stabilization of reefs and coasts (coastal wetlands restoration and valuation, kelp and salt marsh restoration, and coral restoration)	Australia, Indonesia, and mainland US

used to consider social dimensions related to the marine climate interventions their organization was involved. These included publicly available guidelines, strategies, and federal regulations (n = 10) and best-practice leader websites (n = 3) (see Table S3 for the full list). We analyzed these policy instruments using summative content analysis,[79] where we identified and quantified how the social and ethical dimensions of marine climate interventions were accounted for (Table 3). To explore the treatment of these dimensions in policies, we inductively derived child codes from sentiments that were repeated by multiple respondents to identify content that referenced social and ethical considerations and coded each reference in our qualitative coding scheme (see Table S4).

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Sarah Lawless (sarah.lawless@jcu.edu.au).

Materials availability

Survey and interview instruments are available from the lead contact upon reasonable request.

Data and code availability

The data that support the findings of this study (excluding confidential interviews) are available from the lead contact upon reasonable request. Interview results are confidential in accordance with James Cook University's human ethics approval (ID no. H8845). This paper does not report original code.

Table 5. Key informant interview respondent types (n = 7)

Respondent#	Organization
R1	scientific agency
R2	scientific agency & research consortium
R3	international non-governmental organization (INGO)
R4	research consortium
R5	international non-governmental organization (INGO)
R6	scientific agency & research consortium
R7	research consortium

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AUTHOR CONTRIBUTIONS

Conceptualization: T.H.M., E.M.O., and S.L.; methodology and investigation: E.M.O., S.L., and T.H.M.; analysis: S.L. and E.M.O.; preparation – original draft: S.L.; writing – review & editing: S.L., E.M.O., G.G.G., P.J.C., R.S., R.G., S.P., and T.H.M.; funding acquisition: T.H.M. and P.J.C.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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CRSUS, Volume *2*

Supplemental information

Promoting socially responsible governance of new marine climate intervention

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SUPPLEMENTAL TABLES AND FIGURES

Table S1. Actors identified as leading best-practice in governing and implementing novel marine climate interventions

Organisation type	% of respondents (*n*=99)	Description	Organisations cited by respondents as exemplars
Non-profit organization	32%	Nongovernmental entities operating not for profit within domestic or international domains	The Nature Conservancy; The World Wide Fund for Nature; Fragments of Hope
Governmental environment agency	24%	Agencies responsible for environmental regulation, this includes individual agency regulators and National and State Government environmental departments and bodies	Great Barrier Reef Marine Park Authority; Environmental Protection Authority; South Australian Department of Primary Industries and Regions
Non-government research organization	18%	Universities, research centres or research consortiums	Coral Restoration Consortium; Blue Economy Cooperative Research Centre; Centre for Marine Socioecology (University of Tasmania + CSIRO)
Governmental scientific agency or program	13%	Federally funded scientific agencies and/or programs	Commonwealth Scientific Industrial Research Organisation, National Oceanic and Atmospheric Administration, Australian Institute of Marine Science, Reef Restoration and Adaptation Program (Australian Government)
Inter-governmental agency	7%	Regional secretariats and global agencies supporting national level environmental governance	Food and Agriculture Organisation of the United Nations; United Nations Environment Program; The Pacific Community; International Coral Reef Initiative
Community-based organization	4%	Traditional owners, community groups or Indigenous consortiums	Local Marine Managed Areas Network; Indigenous Peoples' and Community Conserved Areas and Territories Consortium
For-profit organization	2%	Business that is for profit and not owned or controlled by the Government	SeaGen; Wavelength

Table S2. Five categories of marine climate interventions survey respondents (*n*=243; *n*=number of responses) (adapted from Morrison et al., *in review*)

Intervention category	Intervention sub-type	Definition	Additional details
Coastal and marine restoration (*n*=106)	Catchment habitat restoration (*n*=3)	Interventions promoting recovery of terrestrial and freshwater habitats to support downstream recovery of marine and coastal populations	Assisted (passive) recovery: Support for the recovery of a population through removal of disturbance, stressors, competitors, or predators Active restoration: Support for recovery of a population through transplanting juveniles or adults from other sites or seeding sites with lab reared individuals
	Natural stabilization of reefs and coasts (*n*=20)	Interventions promoting the stabilization of substrates, reefs, and coastal habitats	Support natural reef and coastal recovery and reinforcement via active restoration and substrate reinforcement using natural materials such as plants, sand, or rock
	Regrowing targeted coastal and underwater species (*n*=83)	Interventions promoting recovery of marine and coastal populations	Assisted (passive) recovery: Support for the recovery of a population through removal of disturbance, stressors, competitors, or predators Active restoration: Support for recovery of a population through transplanting juveniles or adults from other sites or seeding sites with lab reared individuals
Marine bioengineering (*n*=95)	Artificial habitat manipulation (*n*=55)	Introduction of manufactured structures to oceans to provide specific ecosystem function, or support species and/or communities through survival, growth, and reproduction	Artificial habitat deployed on seabed, in water column or in coastal zone
	Assisted evolution (*n*=31)	Acceleration of rate of naturally occurring evolutionary processes to produce climate resilient individuals	Conditioning: Expose organisms to stress to prompt acclimatization within and between generations Selective breeding: Selection for climate resilience. Microbial and symbiont manipulation: Inoculation of early coral life stages with climate resilient microbes and algae
	Assisted migration and colonization (*n*=5)	Human-assisted spread of climate adapted genotypes into populations sensitive to climate change impacts	Assisted gene flow: Movement of adults, larvae, or gametes into at-risk populations within current species range Assisted colonization: Movement beyond current species range
	Controlling climate	Controlling populations of	Removal: Individuals collected and removed from ocean

	exacerbated destructive species (*n*=4)	destructive species exhibiting an outbreak or range shift due to climate change	In-situ: Killing individuals via chemicals or physical trauma
Biological marine carbon dioxide removal (*n*=22)	Aquaculture for carbon sequestration (*n*=22)	Cultivation of marine species, typically primary producers, with the primary aim of carbon sequestration	Aquaculture: Seaweed as it grows, contributes to carbon sequestration in sediments below farm Transport: Harvested seaweed is transported offshore and sunk to sequester carbon.
Marine geoengineering (*n*=11)	Artificial upwelling and downwelling (*n*=1)	Creating artificial upwelling to increase productivity in surface waters (analogous to fertilization methods). Creating artificial downwelling to move water saturated with CO2 into deep ocean.	
	Ocean alkalinity enhancement (*n*=1)	Adding alkaline material to coasts and oceans to modify seawater chemistry. This increases capacity of seawater to dissolve and store carbon dioxide.	
	Ocean fertilization (*n*=3)	Adding nutrients to nutrient-poor regions to promote biological productivity and thus increase the rate at which CO2 is removed from the atmosphere.	
	Shading and cooling water and habitats (*n*=6)	Solar radiation management either through direct shading of marine habitats or cooling of surface waters	Shading: using cloud brightening, fogging, misting, surface films, reflective particles, micro-bubbles or structures to reduce solar radiation (small-scale shade structures may not be considered as geo-engineering). Cooling: ocean pumping to mix water layers to reduce sea surface temperature
Marine social-institutional capacity building (*n*=9)	Anticipatory marine climate science (*n*=2)	Use of tools for anticipating short- to long-term climate conditions and social-ecological scenarios for marine decision support and adaptive management	Types of tools include predictive models and scenarios, technologies, and apps, delivered through climate information and warning systems, mobile phones, digital literacy and access programs
	Climate adaptive aquaculture management (*n*=1)	Flexibility is introduced into the management of aquaculture through property rights, licensing, and lease conditions to enable managers to respond rapidly to projected changes in the dynamics of marine areas, species, and production models	Adjustment of operations through species selection, nutrition, and other practices, through to supporting industries to move offshore to cooler waters or on land in response to warming waters
	Climate adaptive fisheries management (*n*=1)	Flexibility is introduced into to the management of fisheries through property rights, licensing, and lease conditions to enable managers to respond rapidly to projected changes in the	Adjustment of fishing seasons and fishing practices to accommodate an increasing occurrence of climate driven changes in stocks

		dynamics of marine resources and ecosystems	
	Climate resilient marine protected area management (*n*=3)	Management plans incorporate spatial control of non-climate stressors and dynamics on land and in the sea to minimize climate vulnerability and increase climate resilience	Terrestrial water-quality controls to limit inputs e.g., from excessive agricultural nutrients; extra protection of networks of refugia
	Coastal adaptation community planning (*n*=2)	Community planning accounts for actual or expected climate and its effects, to moderate harm or exploit beneficial opportunities	Plan development includes community consultation. Plan may include mapping, and planning for alternative livelihoods, assisted human migration/transition, relocation of low coastal zone, highly exposed peoples

Table S3. Influential regulations and guidelines to assess and manage the social impacts of new marine climate interventions nominated and discussed by best-practice leaders (*n*=7)

Category of document	Focus of document
Publicly available intervention guidelines	Shellfish reef restoration guidelines
	Kelp restoration guidelines
Organizational strategies and assessments	Community-based human rights guidance
	Stakeholder and Traditional Owner engagement strategy
	Indigenous partnership plan
	Intervention regulatory assessment
Federal regulations	Intervention policy [for specific marine ecosystem]
	Intervention social assessment guidelines
	Intervention risk assessment and permitting guidelines
	Human dimensions assessment and monitoring report

Table S4. Qualitative coding scheme (qualitative data only)

Dimension	Code	Code mentions	Data source survey (s); interview (i), policy (p)	Corresponding manuscript section	Thematic code type / category description (if applicable)
Anticipation	Intervention feasibility	75	s, i	2.2	Predetermined code
	Data types	*35*	s, i	Figure 3	Predetermined code
	Biophysical only	7	s, i		Emergent
	Insufficient social data	6	s, i		Emergent
	Social data from participant feedback	5	s, i		Emergent
	Economic only	4	s, i		Emergent
	Social data unnecessary	4	s, i		Emergent
	Social data too challenging	3	s, i		Emergent
	Social data collected well	3	s, i		Emergent
	Response unclear	3	s		Emergent
	Possible social impacts	*40*	s, i	Supp. Figure S1	Predetermined code
	Social impacts ignored or under considered	14	s, i		Emergent
	Co-benefits for Traditional Owners	6	s, i		Emergent
	Impacts upon industry	4	s, i		Emergent
	Costs of not acting	4	s, i		Emergent
	Human wellbeing (general)	3	s, i		Emergent
	General (unspecified)	2	s		Emergent
	Economic only	2	s, i		Emergent
	Social buy-in	2	s, i		Emergent
	Intervention precedents for other systems	1	s, i		Emergent
	Growing interest in marine CDR	1	s, i		Emergent
	Biased toward positive impacts	1	s, i		Emergent
Dimension	**Code**	**Code mentions**	**Data source survey (s); interview (i), policy (p)**	**Corresponding manuscript section**	**Thematic code type / category description (if applicable)**
Inclusion	Type and purpose of public engagement	163	s, i	2.3	Predetermined code
	Public engagement types	*155*	s	Table 1	Predetermined code
	Proceduralized	45	s		Emergent / Respondents reported deliberation was permitted via pre-existing formal and regulatory processes
	Deliberation unavailable	44	s		Emergent / Respondents reported no deliberation opportunities were available
	Unsure	16	s		Emergent / Respondents were unsure if deliberation opportunities were available
	Unspecified	12	s		Emergent / Respondents reported unspecified deliberation opportunities available
	Active	12	s		Emergent / Respondents reported opportunities for intervention co-production
	Reactive	9	s		Emergent / Respondents reported deliberation was up to the public to instigate
	Intermittent or undefined	9	s		Emergent / Respondents reported deliberation opportunities as unclear or intermittent
	Restrictive or purposive	6	s		Emergent / Respondents reported deliberation as only accessible to certain groups
	Exclusive and/or inaccessible	2	s		Emergent / Respondents reported deliberation as restricted with little opportunity to change the trajectory of intervention pathways
	Purpose of public engagement	*8*	i	2.3	Predetermined code
	To be responsive to local priorities and needs	3	i		Emergent
	To gain social licence to operate	2	i		Emergent
	To overcome intervention roadblocks	1	i		Emergent
	To assist with intervention selection	1	i		Emergent
	To ensure free, prior and informed consent	1	i		Emergent
Dimension	**Code**	**Code mentions**	**Data source survey (s); interview (i), policy (p)**	**Corresponding manuscript section**	**Thematic code type / category description (if applicable)**
Reflexivity	Leadership, responsibility and competency for social impacts	120	s, i	2.4	Predetermined code
	Best practice leaders	*99*	s	Supp. Table S1	Predetermined code
	Non-profit	31	s		Nongovernmental entities operating not for profit domestically or internationally
	Governmental environment regulator	24	s		National or state agencies responsible for environmental regulation
	Research-based	18	s		Universities, research centres or research consortiums
	Governmental scientific agency/ program	13	s		Federally funded scientific agencies and/or programs
	Inter-governmental agency	7	s		Regional and global agencies supporting national environmental governance
	Community-based	4	s		Traditional owners, community groups or Indigenous consortiums
	Private enterprise	2	s		Business that is for profit and not owned or controlled by the Government
	Distribution of moral labour	*14*	i	Table 2	Predetermined code
	Delegated or abrogated	7	i		Emergent / Informants described moral labor that is reassigned or ignored
	Lack of moral and ethical resources and expertise	3	i		Emergent / Informants described a lack of moral and ethical resources and expertise
	Urgency to act	2	i		Emergent / Informants described narratives about the 'urgency to act' on climate change, overriding moral and ethical deliberation
	Transferred to other parties	2	i		Emergent / Informants described preference to transfer social responsibility to others
	Diffused and shared	4	i		Emergent / Informants described moral labor that is outsourced
	Other capacity building partnerships	3	i		Emergent / Informants described partnerships for capacity building, knowledge sharing, and local ownership
	Social science partnerships	1	i		Emergent / Informants described deliberative partnerships for social science expertise
	Internalized	3	i		Emergent / Informants described moral labor as intentionally considered and actioned
	Organizational structures, principles and processes	3	i		Emergent / Informants described internal measures to account for moral labor
	Social and ethical capacity and expertise	*7*	i	Figure 5	Predetermined code
	Internal Indigenous partnerships team	1	i		Emergent
	Independent members on board and steering committee	1	i		Emergent
	Engagement with economists	1	i		Emergent
	Engagement with Indigenous partnerships team	1	i		Emergent
	External social science expertise	1	i		Emergent
	Internal GEDI team	1	i		Emergent
	Internal social safeguards expert	1	i		Emergent
Dimension	**Code**	**Code mentions**	**Data source survey (s); interview (i), policy (p)**	**Corresponding manuscript section**	**Thematic code type / category description (if applicable)**
Responsiveness	Oversight to assess and manage social impacts	253	i, p	2.5	Predetermined code
	Formal oversight (policies and regulations)	*239*	i, p	Supp. Table S3	Predetermined code
	Minimise social damage and risk	184	p		Emergent
	Consideration of social, economic, and heritage values	39	i, p		Emergent
	Do no social harm	10	p		Emergent
	Internal social / community guidance for organizations	6	p		Emergent
	Organisational oversight (voluntary)	*14*	i	Figure 5	Predetermined code
	Protocols for responsible exits	3	i		Emergent
	Protocols for ensuring accountability to rights-holders	2	i		Emergent
	Indigenous engagement strategy	2	i		Emergent
	Indigenous engagement guidance (panned)	2	i		Emergent
	Human rights guidance	2	i		Emergent
	Community-led intervention guidance	1	i		Emergent
	Open access intellectual property	1	i		Emergent
	Internal ethics processes	1	i		Emergent

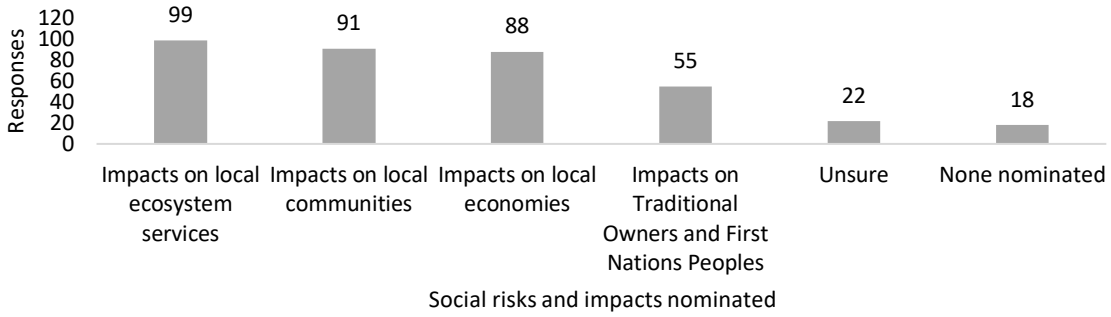

Figure S1. Social risks and impacts of marine climate interventions nominated by survey respondents (total respondents n=164*; number above columns*=number of responses with selection of multiple responses permitted)