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Novel marine-climate interventions hampered by low consensus and governance preparedness

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Emily M. Ogier[1,2] ✉, Gretta T. Pecl[1,2], Terry Hughes[3], Sarah Lawless[3,4], Cayne Layton[1,2], Kirsty L. Nash[2,3] & Tiffany H. Morrison[3,5,6]

Novel marine-climate interventions are now being rapidly implemented to address both the causes and consequences of warming oceans. However, the governance implications of proposed upscaling of such interventions are uncertain. We conduct a survey of 332 intervention practitioners, revealing five types and 17 sub-types of interventions proposed or deployed in 37 marine systems globally. Most (71%) report marine-climate interventions aimed at supporting species and ecosystem adaptation, with 29% aimed primarily at climate mitigation and societal adaptation. Perceptions of climate benefits vary widely, with low consensus across practitioners on the climate goals of specific interventions. Intervention decision-making also remains focused on technical feasibility to meet minimum permitting requirements, with limited appraisal and management of broader ecological, cultural and social risks and benefits of intervention. Practitioners also warn that many marine-climate interventions are currently being tested and deployed in an under-regulated pseudo-scientific bubble.

The need to act in response to projected future ocean warming and ocean change has risen on the global scientific and political agenda[1,2]. Direct climate-driven changes in marine social–ecological systems range from ecological effects, such as changes in species distribution, abundance or community biodiversity[3], to social, cultural and economic impacts on marine-dependent societies, such as reduced food and livelihood security[4]. These changes (for example, 3% per decade loss in fisheries replenishment and >US$800 million in direct economic loss from individual marine heatwave events) are now being observed at unprecedented scale and intensity in marine systems[5–7].

Such rapidly changing conditions form a clear and urgent mandate for novel interventions to sustain marine ecosystems and dependent societies[2,8–10]. Marine interventions can be understood as deliberate, planned actions in marine systems to achieve desired outcomes or goals. Historically, marine interventions have been designed to conserve and restore species or local ecological communities and the ecosystem services they generate[11,12] or improve coastal community well-being through securing rights and strengthening livelihoods[13,14]. Interventions to substantively contribute to climate goals such as mitigation or adaptation have been either secondary or absent.

Today, oceans are on the front line of new planned climate actions. These interventions are novel both in their deployment of new and often untested technologies (for example, genomics, altering ocean biogeochemistry, rights-based frameworks) and in new oceanic, climatic and social conditions. In pursuing climate mitigation, the ocean is now a frontier for both clean energy creation (for example, offshore wind energy) and carbon removal (for example, ocean alkalinity enhancement)[15,16] required to meet the Paris Agreement[17]. In enabling climate adaptation, high-profile interventions include protecting climate refugia to conserve specific marine ecosystems[18], climate

[1]Institute of Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia. [2]Centre for Marine Socioecology, University of Tasmania, Hobart, Tasmania, Australia. [3]College of Science and Engineering, James Cook University, Townsville, Queensland, Australia. [4]Australian Institute of Marine Science, Townsville, Queensland, Australia. [5]School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Parkville, Victoria, Australia. [6]Environmental Policy Group, Wageningen University Research, Wageningen, the Netherlands. ✉e-mail: Emily.Ogier@utas.edu.au

Table 1 | Governance challenges of marine-climate intervention risks

Intervention risk	Outcome	Scale of outcome	Illustrative stories
Ineffectiveness	Failure to achieve stated marine-climate mitigation or adaptation goal	Local/community scale of deployment	30,37,46,91,92
Harm	Unintended cultural, social or ecological harm	Local/community scale of deployment	93–95
Negligence	Further harm due to responsibility gaps in amelioration or restitution of intervention harms	Local/community scale of deployment	49,96
Distrust	Public distrust/rejection of intervention	Local/community scale of deployment	32
		Global/system-wide	33,97
Opportunity cost	High opportunity cost/crowding out of other critical collective actions for marine-climate mitigation or adaptation	Local/community scale of deployment	9,98
		Global/system-wide	56,83,84,99

Scale refers to scale at which outcome is directly observable.

adaptation planning for coastal communities (for example, the Samoa Ocean Strategy 2020–2030 (ref. 19)), adaptation of marine management (for example, adaptive fisheries management plans[20]) and adaptation of specific marine ecosystem processes (for example, breeding thermally tolerant marine species genotypes[21]).

However, systematic and comparative understanding of marine-climate intervention development and deployment remains critically low[22]. In particular, there has been limited empirical investigation of the 'pacing problem'[23] whereby innovation outpaces governance preparedness to anticipate and responsibly manage risk across the range of novel marine-climate interventions currently active or under consideration[22,24–27]. Governance preparedness involves public and private institutions and actors engaged in processes of responsible rule, steerage and guidance[28]. Any lag in the responsiveness of governance regimes is problematic because the rapid emergence and planned upscaling of novel marine-climate interventions[29] presents an array of risks for marine ecosystems[30,31] and coastal societies and rightsholders[22,32,33] at local, regional and climate system and climate policy scales (Table 1). Implicated governance action arenas include marine and coastal conservation, tenure and rights of local communities, small-scale fishers and Indigenous peoples, ocean economy development and decarbonization.

To track the extent to which governance arrangements are keeping pace with novel marine-climate interventions, we surveyed 332 practitioners. We used an online questionnaire to survey the emerging global community of intervention practitioners to ascertain what types of interventions are being planned or deployed, how interventions are being designed, their geographic distribution and stage of development, types of climate goals and benefits pursued and arrangements to responsibly govern intervention. On the basis of our results, we developed a typology of major types and sub-types of novel marine-climate interventions and cross-referenced them against recent authoritative studies (for example, reviews by the National Academies of Sciences, Engineering, and Medicine[10,34]).

In ascertaining the degree to which responsible governance arrangements were present, we adapted and extended existing frameworks for responsible research and innovation to the governance realm. To date, the need for responsible research and innovation (as set out by refs. 31,35) has been met largely by developing codes of conduct for specific types of experimental research (for example, scientific codes of conduct for research on marine carbon dioxide removal[30,36–38]). While such scientific codes are necessary[39–42], they have limited remit or powers beyond experimental-scale research on single types of interventions. The additional governance necessary to facilitate and steer deployment of innovations at scale—to both ensure no undue harm and deliver ecological and social benefits (that is, 'responsible governance')—is less well understood[43–45].

To understand the challenges and opportunities for responsible governance of interventions, our analysis extended these responsible research and innovation frameworks by matching common operational marine governance arrangements with intervention risks. Examples of such governance arrangements include frameworks for assessing feasibility, risk and impact[46,47], mechanisms for public appraisal[48,49], operational oversight[30,50] and marine-climate policy leadership[33,51,52]. Common risks of marine-climate interventions include ineffectiveness relative to desired goal, social–ecological harm, negligence in addressing harm, public distrust of interventions and opportunity cost in intervening (Table 1 and Supplementary Table 1).

Our typology of interventions and framework of governance preparedness enabled us to identify, compare and synthesize key challenges and opportunities in ensuring responsible governance of interventions. In doing so, our intended audiences are policymakers, financiers and scientists engaged in intervention design, decision-making, investment and implementation. Such insights are urgently needed by these groups to facilitate the strategic selection, deployment and ongoing oversight of appropriate interventions at the scale required to sustain marine estates and coastal communities throughout the changing climate.

Results

From our survey sample of 332, we found that the emerging global community of intervention practitioners was dominated by intervention scientists (58%), followed by intervention policymakers (14%) and non-governmental organization (NGO) practitioners (14%). Representatives of Traditional Owners and First Nations and of local community or industry sectors accounted for 1% and 3%, respectively, of our sample. Respondents' engagement in marine-climate interventions ranged from involvement in research development, deployment and monitoring (63%) to programme design, project management and site implementation (13%), policy development, regulation and oversight (10%), funding (4%) and other (9%).

Not-for-profit organizations, government agencies and science organizations were identified as leaders of intervention best practice by survey respondents (38%, 31% and 30% respectively, $n = 82$).

Intervention types and awareness

We found an array of marine-climate interventions being proposed, trialled and deployed globally (Table 2). Practitioners' awareness of novel marine-climate interventions varied substantially across the types and sub-types identified (Table 2). Overall, practitioners were most aware of interventions concerned with marine bioengineering and coastal and marine restoration. Awareness was highest for artificial habitat manipulation (79%, $n = 332$), a sub-type of marine bioengineering intervention, followed by regrowing targeted underwater species

Table 2 | Types and levels of awareness of novel marine-climate interventions (*n*=332 respondents)

Type	Detail	Sub-type	Awareness (%)
Marine geoengineering	Manipulation of the oceanic and atmospheric climate to increase uptake and removal of atmospheric carbon or mitigate direct heating effects	Shading and cooling water and habitat	40
		Ocean fertilization	3
		Ocean alkalinity enhancement	2
		Artificial upwelling and downwelling	2
Marine bioengineering	Manipulation of marine evolutionary processes and ecosystem function and condition	Artificial habitat manipulation	79
		Assisted evolution of marine species	66
		Assisted migration and colonization of marine species	34
		Controlling climate-exacerbated destructive species	2
Coastal and marine restoration	Repairing a climate-impacted catchment-to-marine ecosystem or population	Regrowing targeted underwater species	76
		Regrowing targeted coastal species	66
		Natural stabilization of reefs and coasts	62
		Catchment habitat restoration	1
Marine social–institutional capacity building	Enabling communities and organizations to make marine-climate decisions and redress climate impacts	Anticipatory marine-climate science	1
		Climate-resilient marine protected area management	1
		Coastal adaptation community planning	1
		Climate-adaptive fisheries management	1
Biological marine carbon dioxide removal	Creation or restoration of carbon sinks from natural marine resources	Aquaculture for carbon sequestration	56

Five broad intervention types were apparent: marine geoengineering, marine bioengineering, coastal and marine restoration, marine social–institutional capacity building and biological marine carbon dioxide removal. Within these five broad types, 17 sub-types were apparent on the basis of their treatment and primary goal (that is, restorative in the case of coastal and marine restoration; adaptive in the case of marine bioengineering) and their focal sub-system (that is, catchment-to-ocean in the case of coastal and marine restoration; air–ocean exchange processes in the case of marine geoengineering). See Supplementary Table 2, for detailed typology.

(for example, coral and kelp), a sub-type of coastal and marine restoration intervention (76%). Other sub-types of interventions with elevated levels of awareness included regrowing targeted coastal species (for example, mangroves), assisted evolution of marine species (for example, coral hybridization) and natural stabilization of reefs and coasts (66%, 66% and 62%, respectively). By contrast, awareness of marine geoengineering interventions was low, with the notable exception of interventions to shade and cool water and habitat (40%). Awareness of marine socio-institutional capacity-building interventions was exceptionally low (4%) (Table 2).

Intervention scientists and intervention policymakers had the greatest breadth of awareness of different types of interventions (5.1 and 5.0 types, respectively, on average), while NGO practitioners, representatives of Traditional Owners and First Nations and of local community or industry sectors were aware of relatively fewer (3.9, 4.3, 3.3 and 4.8 types, respectively). Due to the emergent nature of the intervention community and likely standard error, the results of our survey offer an initial exploratory analysis of the range of intervention practitioners, types and locations.

Geographical distribution and stage of development

Interventions were occurring in multiple regions globally, noticeably clustered in locations that are warming faster than the global average (that is, marine hotspot locations; see ref. 53). Respondents reported in detail, interventions ($n = 309$) that are distributed across 37 different specific marine or coastal locations and in most oceans and major seas (Fig. 1a).

Oceans and seas where reported intervention activity was greatest were Australia's tropical waters (16%), Australia's and New Zealand's temperate waters (15%), the North Pacific (15%) and the wider Caribbean (10%). Almost all of the interventions reported as active in Australia's tropical waters were occurring in the Great Barrier Reef region (92%). These interventions were predominantly to support coral reef restoration, for example, through re-seeding coral, breeding of heat-resistant coral symbionts and coral reef habitat restoration and creation (6%, 4% and 2% of all reported interventions). Multiple types of interventions active within the same ocean region were reported almost without exception, with 96% of the interventions occurring in the same ocean region as at least one other type of intervention (Fig. 1b).

In terms of development, the majority of interventions identified were at pilot or full implementation stage (46% and 38%, respectively, $n = 207$ interventions; Fig. 1c) while 16% were at concept stage. Development was most progressed for marine bioengineering and coastal and marine restoration interventions. Specific interventions reported as having the highest level of technical readiness and development included artificial manipulation of habitats and regrowing of targeted coastal species (53% and 65% at implementation stage, respectively; Fig. 1c).

Stated climate goals

Climate goals pursued through marine intervention included both mitigation and adaption, alongside non-climate goals (that is, biodiversity protection). The most stated climate goal was to increase the biophysical adaptation or resilience of local marine ecosystems to climate-driven changes (57% of interventions, $n = 211$; Fig. 2). This climate goal was being pursued across all five intervention types, most commonly through coastal and marine restoration (for example, kelp forest and seagrass bed restoration), followed by marine bioengineering (for example, assisted evolution of coral). Notably, biophysical adaptation and resilience was also being pursued through marine socio-institutional capacity building (for example, development of climate-adaptive fisheries management regimes). However, the goal

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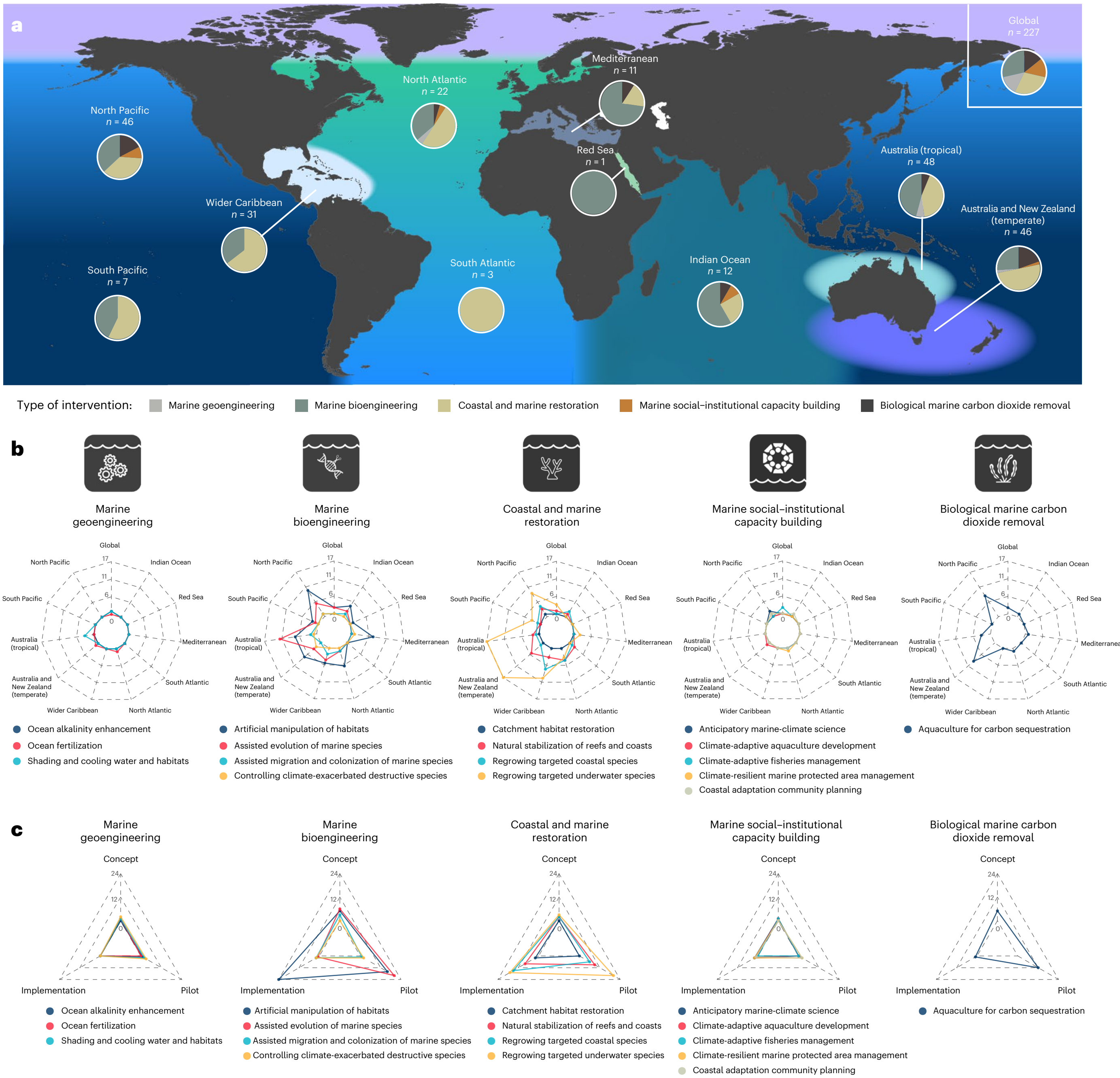

Fig. 1 | Global distribution and development of marine-climate interventions. a,**b**, Global distribution ($n = 309$ interventions) across ocean regions by major types (**a**) and sub-types (**b**). **c**, Stages of development ($n = 207$ interventions) by marine-climate intervention sub-type. Panel **a** generated using rnaturalearth v.1.0.1.9000.

of social adaptation and resilience to climate change was reported for only 3% of interventions. For 5% of the interventions described, no climate goal was identified despite the survey design, which focused on interventions in the context of climate-driven change in oceans (Fig. 2).

Climate mitigation was also being pursued across all intervention types, with carbon removal (rather than emissions avoidance, for example) the second-most stated goal (27%; Fig. 2). Mitigation interventions ranged from those designed to intervene in carbon cycles via marine geoengineering (for example, ocean alkalinity enhancement to increase air–ocean carbon exchange) to those working on biological mechanisms of carbon sequestration (that is, aquaculture for carbon sequestration). Some respondents also reported marine bioengineering (for example, heat-resistant kelp breeding programmes) and coastal and marine restoration (for example, seagrass meadow restoration) as aiming for carbon sequestration as a secondary goal.

For some interventions, there was substantial variation in the climate goals identified. For example, for artificial habitat manipulation, stated climate goals included increasing biophysical adaptation and resilience (58%), carbon removal (19%), no climate goal (19%) and increasing social adaptation and resilience (2%; Supplementary Table 3). Similarly, for regrowing coastal and underwater species, the variety of stated climate goals included increasing biophysical adaptation and resilience (63%), carbon removal (27%), no climate goal (5%), increasing social adaptation and resilience (3%) and raising climate awareness (1%; Supplementary Table 2).

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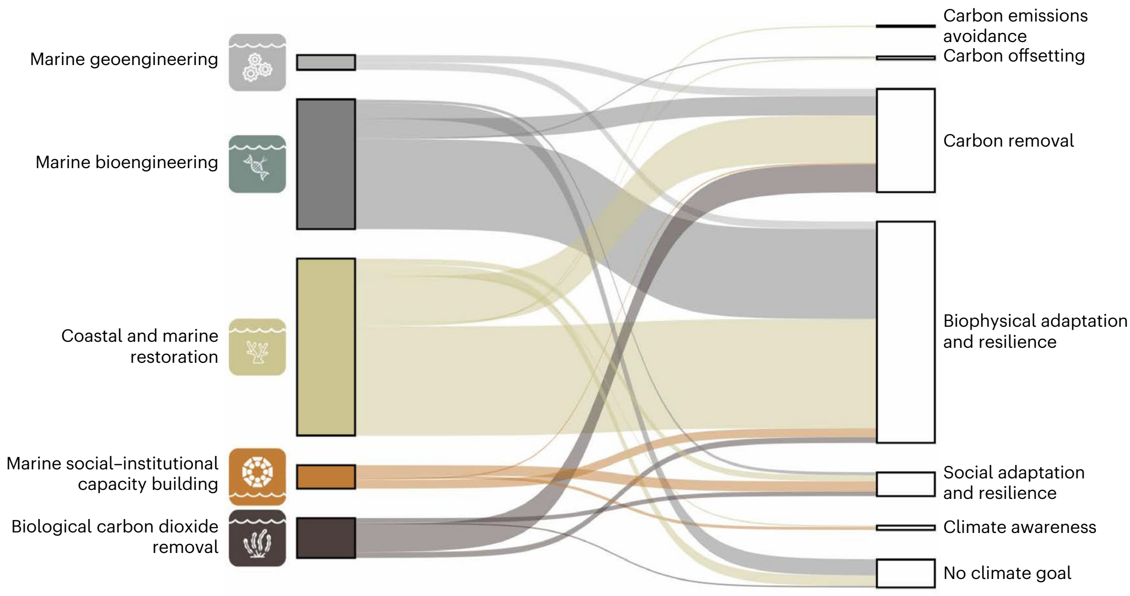

Fig. 2 | Climate-related goals of marine interventions identified by survey respondents (n = 211 interventions). Width of strand indicates the number of interventions for which goal was identified. More than one goal could be identified for each intervention described. See Supplementary Table 3 for a detailed list of goals.

Governance of intervention risk

Gaps in the use of available governance arrangements were notable (Fig. 3) and included the low use of data co-produced with Indigenous Peoples and Local Communities (11% of interventions identified, n = 233), ethics assessment (14%), accountability and transparency mechanisms (15%), social impact mitigation measures (15%) and mechanisms to recognize and address unintended social impact (21%), and strategic leadership capacity (19% of interventions) (Supplementary Table 4).

Preparedness to responsibly govern specific intervention risks (Table 1 and Supplementary Tables 5 and 10) was varied. The risk of ineffectiveness was the risk most frequently addressed by applying available government arrangements. Levels of use across the available arrangements ranged between 57 and 70% of all interventions, from use of multiple data types (70% of interventions) and data sources for feasibility assessment (65%) to multiple forms of assessing implementation risk (59%; Supplementary Table 4).

By contrast, levels of use of available arrangements to govern the risk of unintended harms ranged between 32 and 50% of interventions. Levels of use of available arrangements to govern risks of public distrust in interventions were even lower (between 28 and 50%), and for risks of negligence in addressing intervention effects, the range was lower again (between 28 and 35%). Concerningly, arrangements to govern the risk of opportunity cost in pursuing a given intervention were present in only 19% of interventions, implying that most interventions are not being assessed against one another (Supplementary Table 4).

Unsurprisingly, marine social–institutional capacity building was the intervention type where responsible governance arrangements were most frequently applied across all risks (44% mean level of presence). Arrangements for governing risks of ineffectiveness, harms, negligence, distrust and opportunity cost were present at rates of 63%, 50%, 50%, 32% and 30%, respectively. By contrast, marine bioengineering was the type of intervention for which responsible governance arrangements were least often in place (33% mean level of presence across all risks; Supplementary Table 6).

In reporting on the risks and opportunities of an intervention, practitioners (n = 130) held divergent positions on the necessity of further responsible governance arrangements. While 23% of practitioners called for increased levels of governmental appraisal, planning, coordination and regulation, a contrasting 16% called for reduction of such arrangements, which they perceived to be hindering rates of implementation and upscaling. Practitioners requesting strengthened governance asked for increased rigour in technical feasibility, risk and impact assessment (25%), increased policy and community support, including funding (22%), reduced scientific uncertainty combined with increased science coordination (7%), increased climate mitigation and mechanisms for addressing other underlying stressors (4%) and greater inclusion of Indigenous Peoples and Local Communities (3%).

Discussion

An open question in marine-climate research is what the proposed upscaling of novel marine-climate interventions means for climate action and long-term well-being of marine systems and marine-dependent people. Most governance arrangements in place are limited to formal risk assessments and regulatory and permitting processes[27,54,55] based on retrospective understandings and technologies operating under high levels of uncertainty[56]. The observed low level of governance preparedness to responsibly govern the risks posed by novel and experimental marine-climate interventions indicates that the pacing problem is indeed present. Responsible governance regimes are needed to avoid risks of maladaptation and the potentially high opportunity cost of marine-climate interventions. Fortunately, gaps in responsible governance constitute a resolvable problem where public-interest actors have principles to guide them and, increasingly, the operational arrangements and practices to mandate and use[35,36]. Our analysis of practitioner observations highlights multiple reasons for and opportunities to address this gap.

First, marine-climate intervention remains science driven with limited involvement of public institutions or communities and only 14% of practitioners in our sample working within government. By contrast, the biophysical science sector's major role in novel intervention development and in standard-setting for intervention research is likely to explain the emphasis on technical feasibility assessment as the main form of intervention appraisal. The relative absence of strong public-interest actors and processes, combined with the limited competencies of conventional science organizations[39–42,57], may also explain the low levels of use of responsible governance arrangements (Fig. 3). Not surprisingly, organizations in the NGO and research

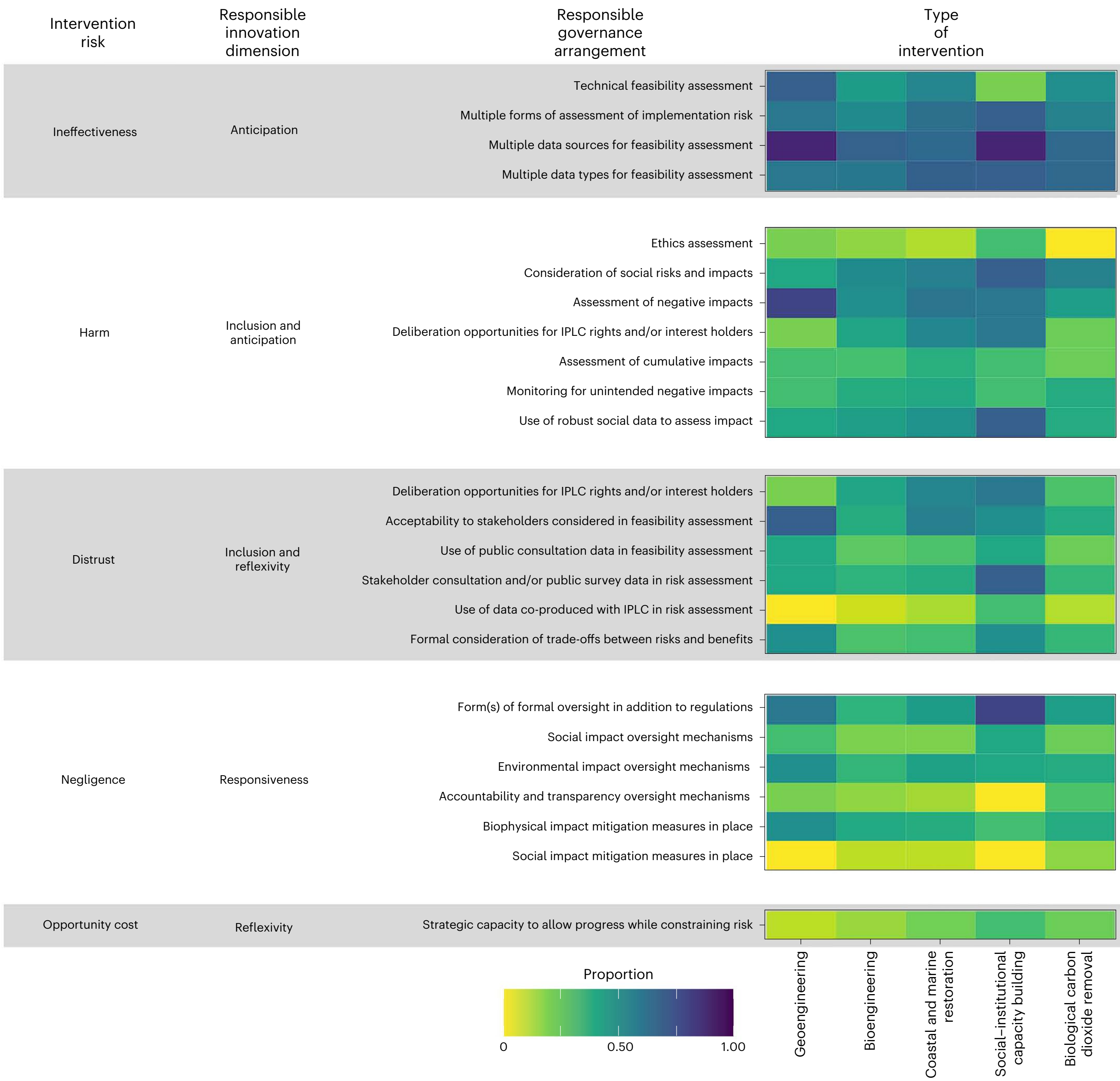

Fig. 3 | Use of responsible governance arrangements to manage anticipated risks of novel marine-climate interventions (n = 233 interventions). See Supplementary Tables 1 and 5 for definitions and data. IPLC, Indigenous Peoples and Local Communities.

sectors were recognized as best-practice leaders of interventions by 68% of the survey respondents. Actors within these networks clearly wield considerable potential influence and include 'impact investors'[58,59], ocean philanthropic funders[60–62], speculators attracted by the establishment of carbon markets[63] and scientists whose formative role in experimentation and intervention innovation renders them de facto governors[35,64]. Engagement of public actors in the formative stages of marine-climate intervention development is critical because of risks of sociocultural harms and the potential high opportunity cost of upscaling. Opportunities to do so include adoption of proven participatory and deliberative early public engagement frameworks (see refs. 65,66) and the use of bioethical assessment frameworks[67] by funders and regulators.

Second, interventions using bioengineering or restorative techniques have the highest level of awareness and were the types of marine-climate interventions with the highest rates of implementation and widest geographic distribution across our sample of 322 practitioners. While other types of marine-climate interventions were reported (for example, marine geoengineering, biological marine carbon dioxide removal, marine social–institutional capacity building), awareness was lower, which is likely to be at least partly explained by their more limited geographical distribution and their development being more commonly at the concept or pilot stage. Funders and public policy decision-makers charged with large-scale climate action face choices between available marine-climate interventions. The information asymmetry between intervention types observed in our study may limit the possibility of decision-makers being able to make informed choices among the full range of viable interventions. Increasing marine-climate action literacy among decisions-makers is a critical means of addressing this challenge, starting with sharing of more accessible science-based information about climate action options (for example, Reef Adapt tool (https://www.reefadapt.org)).

Third, despite the low awareness of interventions to build social and institutional capacity for climate adaptation and mitigation detected in our results, these intervention types warrant additional consideration. The intervention examples reported by survey respondents highlighted important ways forward, including restitution and formalization of marine and coastal tenure for Indigenous Peoples and Local Communities, partnerships in climate intervention science programmes and coastal adaptation planning with local communities. Our results also revealed that practitioners are increasingly recognizing the need for social–institutional capacity to reduce intervention risks of sociocultural harms, negligence and distrust. Social–institutional capacity can be built through rights-based frameworks (see refs. 68–71 and the Turning Tides facility (https://turningtidesfacility.org)) and regional and community-led programmes for coastal climate adaptation planning (see ref. 72) and by enabling local rule-making for climate action (see ref. 35). Such institutions support a priori recognition of equity, cultural rights and interests before conceptualization and assessment of an intervention. By coupling regional and local-scale socio-institutional capacity-building interventions with local bioengineering, geoengineering and restorative interventions, such initiatives could be 'bright spots' in which social, cultural and biophysical goals are mutually recognized and pursued (see refs. 14,20,72,73).

Fourth, marine-climate interventions are occurring in all major ocean regions, and within each of these regions more than one specific intervention sub-type is under way. For example, in the North Atlantic and in tropical waters adjacent to Australia, the range of interventions described includes those in all intervention types. This co-occurrence may present additional under-recognized governance challenges for policy- and decision-makers who are faced with both prioritizing across interventions and managing their cumulative and synergistic impacts within a single marine region. We found that formal consideration of trade-offs between intervention risks and benefits and assessment of cumulative impacts are not widely occurring governance practices (reported as occurring for only 31 and 32% of interventions, respectively). The results suggest that many decision-makers are materially underprepared for these strategic challenges, which extend beyond managing the risks posed by single interventions[22,30,32]. Tools such as anticipatory social and cumulative impact assessment frameworks[74,75] are available to support decision-makers to integrate their assessment and management of discrete climate actions into broader strategic assessment and planning at the marine estate or regional communities' level (for example, the IPCC's shared socioeconomic pathways[76], which could be adapted for marine regions).

Fifth, our results highlighted that systematic and comparative assessment of marine-climate interventions continues to be confounded by a lack of clarity and low consensus in stated climate-related intervention goals. In some cases, interventions such as seaweed afforestation were reported to be pursuing both climate mitigation and adaptation goals simultaneously. We observed frequent use of the term 'resilience' by many practitioners in self-reporting the ecological and social goals and benefits of their chosen intervention in lieu of providing more intervention-specific detail to which they were invited. Resilience has been widely critiqued for being conceptually vague, ignoring power and politics, and being operationally weak[77,78]. This lack of clarity on resilience obfuscates efforts to assess effectiveness of interventions and fails to deal with power asymmetries and inequity in pursing climate actions[79]. Rectifying this lack of climate goal precision (and therefore accountability) will depend on funders and public-interest actors demanding uptake of principles and codes of practice (see High-Quality Blue Carbon Principles[80]) and, increasingly, standards for monitoring, reporting and evaluation of specific intervention effects[30,37,81,82].

Finally, practitioners themselves are among those who query the rigour of technical feasibility assessment and evaluation of impact of interventions against intended and claimed benefits and co-benefits. One-quarter of survey respondents raised these concerns. Indeed, emerging social science suggests that entrepreneurial hype combined with an absence of strong monitoring, evaluation and reporting requirements can produce perverse outcomes whereby speculative interventions are prioritized over effective ones[8,63,83–85]. Our results underscore that claims of multiple conservation and climate goals and co-benefits combined with low levels of technical feasibility assessment (50% of reported interventions) and very low levels of accountability and oversight (16%) and strategic capacity to steer innovation and manage marine-climate intervention risk (18%) increase the likelihood of poor choices, contributing to both unintended negative consequences and missed opportunities in climate mitigation and adaption. The practitioner concerns are therefore valid, while at the same, it is important to acknowledge that carbon removal and climate adaptation goals may be feasible in some cases for specific species and ecosystems[86].

In conclusion, our global survey and subsequent statistical analysis revealed that, broadly, governance of novel marine-climate interventions is occurring in both a 'scientific bubble' and an 'institutional void'[87,88]. Future research could incorporate inferential analyses to explore distinctions across practitioner groups, regions and jurisdictions and interactions among factors affecting practitioner awareness, intervention impacts and operational governance practices in place. Such analysis would support further development of responsibly governed and context-appropriate marine-climate actions.

Overcoming the pacing problem through timely uptake and formalization of available or emergent responsible governance practices (Fig. 3) requires continued scientific leadership to ensure that technical design, assessment and monitoring of marine-climate interventions is adopted and sufficiently rigorous. At the same time, the bioethical, anticipatory and reflexive requirements of responsible governance demand that many other actors are better engaged alongside these practitioner communities[89]—to build legal and institutional capacities and to ensure that governance of multiple marine-climate interventions is underpinned by climate action and justice principles[90].

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-025-02291-4.

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Methods

Survey instrument design

Observations and attitudes towards novel marine-climate interventions were surveyed using an online survey–questionnaire targeting active practitioners. Questions were designed to capture observational data describing current arrangements for governing interventions and positional attitudinal data concerning perceived benefits and costs, gaps in governance, risks, and missed and emerging opportunities (see survey–questionnaire in Supplementary Table 8). Types of interventions used to design response options were identified from recent authoritative reviews[15,34,84]. The questionnaire used a mix of selected choice questions, ratings and open-ended text response questions. The questionnaire was delivered using Qualtrics[xm] online survey software.

The survey instrument and specific questions were pre-tested by members of the research group, revised and then formally piloted through a soft launch of the survey in October 2022 with members of the study's technical advisory committee.

Ethics statement

The study was approved by the James Cook University Human Research Ethics Committee (approval number H88845) in accordance with the Australian *National Statement on Ethical Conduct in Human Research, 2007 (Updated 2018)*[100], which addresses matters of harm and benefit to study participants. The recruitment method and survey instrument were designed to provide participants with information about the study and obtain informed consent before participation through an initial screening question.

Participant selection and recruitment

Actors engaged in novel marine-climate interventions constitute an emerging group. The survey was designed to target participants in this broad group via their participation in professional networks associated with interventions. Participant selection was therefore opportunistic, and stratified sampling of specific sub-groups, such as Traditional Owners and First Nations, was not pursued[101]. Strategies to limit sample bias included translating the survey–questionnaire into six languages: English, French, Portuguese, Spanish, Japanese and Chinese (Simplified). The survey was distributed to professional networks engaged in a wide range of marine-climate interventions, including marine and coastal restoration, marine conservation, community and small-scale fisher development, marine carbon dioxide removal and other forms of geoengineering, seafood afforestation, solar radiation management, and coastal and marine community adaptation planning. Professional practitioner networks assisting with survey distribution in the later stages of recruitment also included practitioners from the NGO sectors, local community representatives and Traditional Owners and First Nations.

Professional communities approached were invited to respond on the basis of their engagement with 'new and emerging' marine-climate interventions. The survey instrument was designed to collect both descriptive and attitudinal data about the broad array of observed interventions as well as those specific interventions for which respondents had subject-matter expertise and direct professional experience. Examples of interventions were provided in recruitment materials to assist in clarifying the term, and these included assisted evolution, cloud brightening, seaweed farming, coral propagation and translocation. These examples were not exhaustive of a broader range of interventions and may have had limited recruitment of potential respondents engaged in other types of interventions.

Practitioners were recruited for survey through professional open online networks and using published affiliations information. Recruitment methods included general broadcast emails using professional international email lists, published professional email addresses and social media posts in six languages via Twitter using professional accounts. Multiple phases of recruitment occurred in early October 2022, mid November 2022, late January 2023 and early March 2023. The same distribution methods were used with revised recruitment and advertising messages reflecting the stage of the survey and the time left to participate.

Data collection

The online survey–questionnaire was launched on 31 October 2022 and remained open until 15 March 2023. Three hundred and thirty-two responses met the criteria for level of question completion and were retained for analysis. These responses included those undertaken in five non-English languages—Chinese, Japanese, French, Portuguese and Spanish—which accounted for 18% of the final sample. These responses were translated into English by native speakers with marine expertise before analysis.

Survey data were not treated to any weighting to adjust for the expected population because the survey population was an emerging specialist group, and population characteristics were not established. Response rates to the survey by sub-group are therefore not reported. Representativeness of the survey data was therefore subject to sample bias although recruitment methods were adjusted to target non-English speakers in five other languages and practitioners in non-scientific networks. A degree of sample bias was accepted as an expected limitation of the study due to the nature of the emerging group being surveyed and the online survey–questionnaire instrument used[101]. No identifying data were collected from respondents although in some cases participants provided personal identifying data in response to open-text questions.

Data analysis

Two units of analysis were used to examine the data. Data on respondents' role, interaction with interventions and general awareness of interventions were treated as data about the respondents, while data in response to survey question six onwards were treated as data about the intervention the respondent was asked to identify as the one with which they were most familiar.

Selected choice data where respondents answered by selecting from a pre-determined set of options were analysed using basic descriptive statistics (frequency counts). These included questions to identify awareness of interventions, involvement in active intervention planning and deployment, the stage of development of the intervention respondents were most familiar with, the types of actors and organizations engaged in their development and the presence or absence of specific governance arrangements. Open-ended text responses were analysed using thematic content analysis[102–104] to code data and thereby convert the qualitative data into quantitative data. To increase coding reliability[105], first-pass coding frameworks were reviewed and tested by other members of the project team before finalizing and then undertaking the thematic analysis. Basic descriptive statistics (frequency counts) were then used to analyse the coded survey data by theme.

Both selected choice data and open-ended text data describing the types and sub-types of interventions respondents (n = 332 respondents) were aware of and were most familiar with (n = 240 interventions) were initially analysed using a coding framework based on the initial typology we developed from a review of published studies (Supplementary Table 2). Inductive thematic coding of open-text data describing interventions was undertaken using NVivo 20 qualitative research software, and initial type and sub-type codes were subsequently adjusted in response to survey data thematic codes (Supplementary Table 9). These final codes were checked against the choice response the respondents selected for verification and against more recent authoritative reviews (for example, review by the National Academies of Sciences, Engineering, and Medicine[10]) for salience.

Open-ended text data about the location of the identified interventions were analysed using a coding framework developed in Nvivo and organized by oceans and seas described in response data text.

Frequency analysis was then undertaken by intervention type and sub-type using the following identified oceans and seas: North Atlantic, South Atlantic, North Pacific, South Pacific, Red Sea, Mediterranean Sea, Indian Ocean, Wider Caribbean, Australia (tropical), and Australia and New Zealand (temperate).

Open-ended text data in which respondents identified the climate goals of the intervention they were most familiar with were thematically coded using a coding framework developed from the ten intervention climate benefits identified by review of the literature (Supplementary Tables 3 and 10). Frequency analysis was then undertaken by climate benefit code, and data were analysed for distributions of climate goals by intervention type. Open-ended text data in which respondents identified the major risks and opportunities of the identified intervention were thematically coded using a coding framework developed inductively from the data (Supplementary Table 7). Frequency analysis was then undertaken by type of risk or missed opportunity.

To determine the extent of responsible governance of new marine-climate interventions, we developed a methodological heuristic by extending Stilgoe[31] and Macnaghten's[35] framework for responsible innovation (based on anticipation, inclusion, responsiveness, reflexivity), which they apply to emerging scientific innovations and in particular to climate geoengineering innovations. We matched these four dimensions to the new categories of marine-climate intervention risk (Table 1), which we developed from the literature. In extending the responsible innovation framework, we defined responsible governance as rules, guidance and steerage overseen by governing actors to prevent intervention risk. We identified specific examples of such governance arrangements through a review of the literature on instruments and processes for governing technical feasibility, cumulative risk and impact assessment, including public deliberation in intervention development and approval and anticipatory climate governance. These specific governance arrangements were then matched to relevant survey response data fields (Supplementary Tables 1 and 5). Indication of the specific governance arrangements described in survey questions was analysed for each intervention type using basic descriptive statistics (Supplementary Tables 4 and 6).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The raw dataset generated by the survey research is not available due to restrictions to protect study participant privacy and to limit reuse to studies of a similar nature, in accordance with the *National Statement on Ethical Conduct in Human Research, 2007 (Updated 2018)*[100] (James Cook University Human Research Ethics Committee approval number H88845). The processed and de-identified dataset is, however, available from the authors on reasonable request for studies of a similar nature.

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Author contributions

E.M.O. led the literature review, survey design, data collection, survey data analysis and manuscript preparation. G.T.P. contributed to survey design, survey data analysis and manuscript preparation. T.H. contributed to survey design and manuscript preparation. S.L. and C.L. contributed to survey data analysis and manuscript preparation. K.L.N. contributed to the literature review, survey data analysis and visualization. T.H.M. co-led the literature review, survey design and data collection and contributed to the survey data analysis and manuscript preparation.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Emily M. Ogier.

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Corresponding author(s): Emily M. Ogier

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Qualtricsxm online survey program (v. 09.2022)
Data analysis	Qualtricsxm online survey program (v. 07.2023)

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

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The raw dataset generated by the survey research is not available due to restrictions to protect study participant privacy, in accordance with the Australian National Statement on Ethical Conduct in Human Research, 2007 (Update 2018) (approval number H88845). The processed and de-identified dataset is subject to controlled access, whereby access can be permitted for ‘extended’ use of data in future research projects that are either (i) an extension of, or closely related to, the original project; or (ii) in the same general area of research (for example, social research), in accordance with the Australian National Statement on Ethical Conduct in Human Research, 2007 (Update 2018). The authors will respond to requests made via email to make data available within 6 weeks.

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	Not applicable
Reporting on race, ethnicity, or other socially relevant groupings	Groupings of survey participants was reported on the basis of professional engagement with novel marine-climate interventions. Groupings used in reporting results were: scientists; policymakers; Non-Government Organisation practitioners; representatives of Traditional Owners and First Nations; representatives of local community or industry sectors; representatives of industry organisations.
Population characteristics	Practitioners engaged in novel marine-climate interventions constitute a specialist group. The survey was designed to target participants in this group via their participation in professional networks associated with interventions. Participation selection was therefore opportunistic and stratified sampling was not pursued. However, the survey-questionnaire was made available in six languages: English, French, Portuguese, Spanish, Japanese, Chinese (Simplified).
Recruitment	This specialist group was recruited for survey through professional open online networks and using published affiliations information. The survey instrument was designed to collect both descriptive and attitudinal data about the broad array of observed interventions as well as those specific interventions for which respondents had subject matter expertise and direct professional experience. Recruitment methods included general broadcast emails using professional international email lists and social media posts in six languages via Twitter using professional accounts. Professional communities approached were invited to respond based on their engagement with "new and emerging" marine-climate interventions. Examples of interventions were provided in recruitment materials to assist in clarifying the term, and these included assisted evolution, cloud brightening, seaweed farming, coral propagation and translocation. These examples were not exhaustive of a broader range of interventions and may have had limited recruitment of potential respondents engaged in other types of interventions. Representativeness of the survey data was therefore subject to sample bias but this was accepted as an expected limitation due to the nature of the specialist group being targeted and the online survey-questionnaire instrument used.
Ethics oversight	Jame Cook University Human Research Ethics Committee

Note that full information on the approval of the study protocol must also be provided in the manuscript.

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Observations and attitudes to novel marine-climate interventions were surveyed using an online survey-questionnaire targeting active practitioners. Questions were designed using mixed methods to capture quantitative and qualitative observational data describing the state-of-play of governance of interventions and positional attitudinal data concerning perceived benefits and costs, gaps in governance, risks, and missed and emerging opportunities. The questionnaire used a mix of selected choice questions, ratings and open-ended text response.
Research sample	The research sample were practitioners professionally engaged in novel marine-climate interventions, inclusive of funders, research scientists, representatives of First Nations, industry or community groups partnering in interventions, and government agency staff involved in policy development or regulation. The research sample was not representative. Rationale for the chosen research sample was based on the emergence of this professional community and its unknown population size.
Sampling strategy	Opportunistic sampling was used. No statistical methods were used to pre-determine the sample size because the total population of practitioners being targeted for the research was not known (i.e., as an emergent practitioner community). As no sample sizes were chosen, the sample size obtained (n=332) was deemed to be sufficient as thematic saturation was observed in the qualitative responses to open-ended questions.
Data collection	Data was collected via the questionnaire, which was delivered using Qualtricsxm online survey software (v. 09.2022). The questionnaire was completed at the participants' convenience and no researcher was present. Researchers involved in collecting the study data were aware of the study hypothesis. No experimental conditions were used in the research.

Timing	The online survey was conducted continuously between 31/10/2022 - 15/03/2023.
Data exclusions	Two data exclusions were applied, as follows: - Data which was personally identifying (three instances). One instance of this occurred where a participant entered a written text response to an open-ended question which named another researcher. Two additional instances included the respondents providing specific identifying details of their professional roles. - Data entered in response to open-text questions which did not meet data inclusion criteria (79 instances). Specifically, data were excluded where the entries were not recognisable as text and thematic coding was not possible.
Non-participation	The number of participants who did not proceed once informed consent had been indicated via the online survey screening question was 46. This group was not included in the sample for analysis.
Randomization	Participants were not allocated into experimental groups. Reported groups were based on self-selected choice options provided in the questionnaire for type of practitioner.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Clinical data
☒	☐	Dual use research of concern
☒	☐	Plants

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

Plants

Seed stocks	N/A
Novel plant genotypes	N/A
Authentication	N/A