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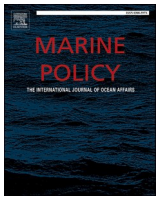

Overcoming lock-in of science-policy responses to reef heating

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ABSTRACT

Marine heating is the long-term climate-induced warming of oceans. Marked by more frequent, longer and widespread marine heatwave events, the severity of marine heating is generating catastrophic impacts on reef peoples and ecosystems. Here, we examine the range of policy solutions proposed to address reef heating. We find that, until recently, science-informed policy solutions were dominated by recommendations for more 'inclusive adaptation' and more 'usable' science. While these are laudable goals, such a narrow and locally-focused set of solutions suggests many researchers, policymakers, and funders have restricted their responses to the highly visible symptoms of reef heating, thereby locking in a particular science-policy pathway. Science-policy lock-in is concerning because it can popularise solutions that place the burden of response on to already vulnerable groups, avoid tackling deeper structural drivers of change, and overlook a wider range of possible solutions. In response, we showcase emerging research trends proposing a broader and more impactful agenda for reef science and policy. Such an agenda is explicitly designed to expand the policy solution space to secure a wider, more effective, and more just range of responses to ongoing marine heating for reef peoples and ecosystems.

1. Introduction

Coral reefs and the human communities that depend upon them are profoundly impacted by marine heating and marine heatwave events [40,56,83]. Climate-induced warming can cause coral to bleach and die, diminishing their capacity to provide fish habitat, coastal protection, tourism livelihoods, cultural identity, social wellbeing and other ecosystem services critical to tropical coastal communities [2,77,9]. Since 1998, marine heatwaves have bleached or killed corals in more than 90 % of reefs listed as World Heritage sites worldwide, including in Hawaii, the Galapagos Islands, and Australia [52]. In the world's largest reef system, the Great Barrier Reef, half the corals died in 2016 and 2017 alone [55]. The impacts of climate-degraded reefs are already being felt by the six million people directly dependent on reef fishing and the additional 400 million tropical coastal peoples reliant on reefs to support their livelihoods and food and nutrition security [104,35]. Many of these tropical coastal communities are in the world's poorest low-income countries and are experiencing marine heating alongside other climate impacts such as rising sea levels, ocean acidification, amplified weather extremes, and water, food, and energy insecurity.

For the past two decades, marine researchers have highlighted these climate challenges. Scientists and policymakers have identified reef communities not only as forerunners in bearing the challenges of climate change but also as important vanguards in developing solutions for mitigation, adaptation and resilience [109,57]. Notably, many marine researchers have sought to directly bridge the gap between climate

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challenges and climate solutions through improved science communication, policy advocacy, and working more closely with decision-makers. Here we examine the solutions to marine heating most proposed by science and policy. We find that the marine heating policy literature appropriately reflects broad calls for 'inclusive adaptation' and 'usable science' across all climate-impacted systems. However, we also find reef heating researchers and policymakers continue to prioritise discrete local problems and interventions over deeper policy challenges and policy solutions. Such a phenomena is understood in the policy sciences as science-policy 'lock-in.'

Science-policy 'lock-in' is a systemic dynamic detectable in both climate and conservation policy, whereby self- or mutually reinforcing mechanisms make science-policy systems stable and resistant to change [31,97]. Instead of considering additional approaches, a science-policy community can circle around a particular conceptual framing and set of related assumptions, which locks them in to attempting a greater quantity or higher level of the same policy solution [44]. While lock-in can be desirable in many instances (e.g., lock-in of renewable energy science and policy), it can also be problematic, especially when lock-in sidelines development of more impactful new approaches. It is important that the reef science-policy community identifies and diagnoses lock-in dynamics for two reasons. First, proper diagnosis can help the field to understand why redirecting science, governance, and management is so difficult. Second, proper diagnosis can help identify targeted ways of 'unlocking' new and potentially more impactful solutions.

Here we review 75 reef policy studies published between 2004 and 2021 to diagnose how the field understands the policy challenges and policy solutions for reef heating. We show that despite the growing maturity of the field, researchers continue to emphasise inclusive adaptation and usable science as preferred policy solutions. While these are critically important goals, we argue that locking-in to these solutions can place the burden of response on already vulnerable groups, avoid tackling deeper structural drivers of change, and overlook a wider range of possible solutions at different scales [74]. To that end, we showcase emerging work already underway to unlock additional solutions. Our aim is to draw together a broader reef science and policy roadmap for marine researchers, practitioners, policymakers and funders designing targeted science, investment and policy action. Given that the International Panel on Climate Change, Ocean Visions and UN Decade of Ecosystem Restoration and Ocean Science for Sustainable Development are now setting the terms for marine heating research and policy in the years immediately ahead, this is a key moment for reef science and policy [98].

2. Methods

2.1. Background and justification of reef governance case

Coral reef science and policy is emblematic of the broader science-policy challenges facing heating marine systems and is also critically important in its own right. The value of coral reef ecosystem services is estimated to be higher than any other ecosystem on Earth, with reefs supporting multiple dimensions of the wellbeing of millions of people in the tropics [104,53,63] and playing an important role in the identity of those living elsewhere [46]. While coral reefs cover only a small portion of the ocean floor almost a third of the world's marine fish species are found on coral reefs, and reef catch constitutes a considerable proportion of fish consumed by humans. In particular, developing economies in Southeast Asia and rural coastal populations in Western Pacific island nations are highly exposed to reef heating [104,66]. Since 2016, increasingly severe back-to-back reef heating events have caused rapid and recurrent shocks for these tropical coastal communities [55], stressing that time is running out to mitigate the worst effects of climate change for the six million reef fishers in 99 reef countries and territories worldwide. Indeed, the IPCC warns that all coral reefs in the world could disappear by 2070 if climate change continues on its current trajectory [57]. Because reef-associated social-ecological systems are a critical (albeit unjust) natural experiment in shock and adaptation, intergovernmental and government policymakers are now looking to reef ecosystems and their peoples as both 'canaries in the coalmine' and potential vanguards for transformation.

2.2. Systematic review method

We undertook a review of the literature to examine science-policy challenges and solutions to marine heating in coral reef systems. A systematic review identifies, synthesises, and evaluates the findings of all relevant empirical studies on an issue. While time-consuming, such an exercise is useful for ascertaining the state of knowledge, biases and gaps in a field. Our search was undertaken in late 2021 on papers published since 2004 (when the first studies began to appear). Scopus and Web of Science searches returned (after removal of duplications) 909 articles that examined coral reefs, climate change and governance (Fig. 1). We specifically wanted to extract empirical articles particular to governance of reef heating and associated acidification. We ran two stages of screening, first to remove studies focussed on genetics and physiology (where reef heating policy challenges and solutions were only mentioned in passing in the conclusion), and a second stage of screening to retain only those articles that were empirical research articles (i.e., excluding reviews or perspectives). We identified 75 empirical articles and subjected them to content analysis.

For the 75 empirical articles, we inductively developed and coded categories for the types of reef heating policy challenges they addressed (e.g., climate and other ecological impacts; social-economic risks of climate impacts; institutional and management challenges; broader governance and political challenges). We also categorised the types of reef heating policy solutions, if any (e.g., improved planning and management; improved organisational capacity; new institutions; better governance). Following [22], we then identified at what scales reef heating policy challenges and solutions fell (e.g., multiscale, trans-national, national, sub-national, local; Tables 1 and 2). We achieved validity and reliability through intercoder checks. We assessed how frequently different policy challenges and solutions were proposed, and charted the relationships between them by identifying whether they were raised in the same paper (Supplementary Fig 1). Policy challenges and solutions were also plotted against categories and scales to identify trends in spread. We then undertook a scoping review of more recent literature (2022-present) to verify and explain our findings, and to explore promising new studies opening up additionally fruitful lines of research.

3. Results: diagnosing science-policy lock-in

Our survey of 75 reef heating policy studies published over the last two decades finds that focused policy analysis of climate challenges for coral reef-dependent communities dates back to at least 2004 (e.g., [107]). Since 2004, reef heating analysts have typically focused on four types of challenges: (i) impacts of climate change and other drivers on reef ecosystems [43] (ii); associated socio-economic risks to reef communities [26,67,88], (iii) local institutional and management challenges [29,7], and (iv) broader policy and governance challenges [10]. Today, reef heating is generating challenges that are not just ecological, but also socio-economic, institutional and political (Fig. 2).

Like the climate adaptation literature more broadly [57], our review revealed a persistent focus on vulnerabilities, deficits, and barriers to change (e.g., [103]), rather than institutional transformation and adaptive capacity building (Fig S1A). Many studies highlighted that local institutions and managing agencies in tropical coastal nations were operating under-capacity relative to the scale and the speed of change in reefs [30,71,78]. They emphasised that, without institutional transformation, government agencies will remain relatively powerless to help sustain reefs and associated human populations through a changing

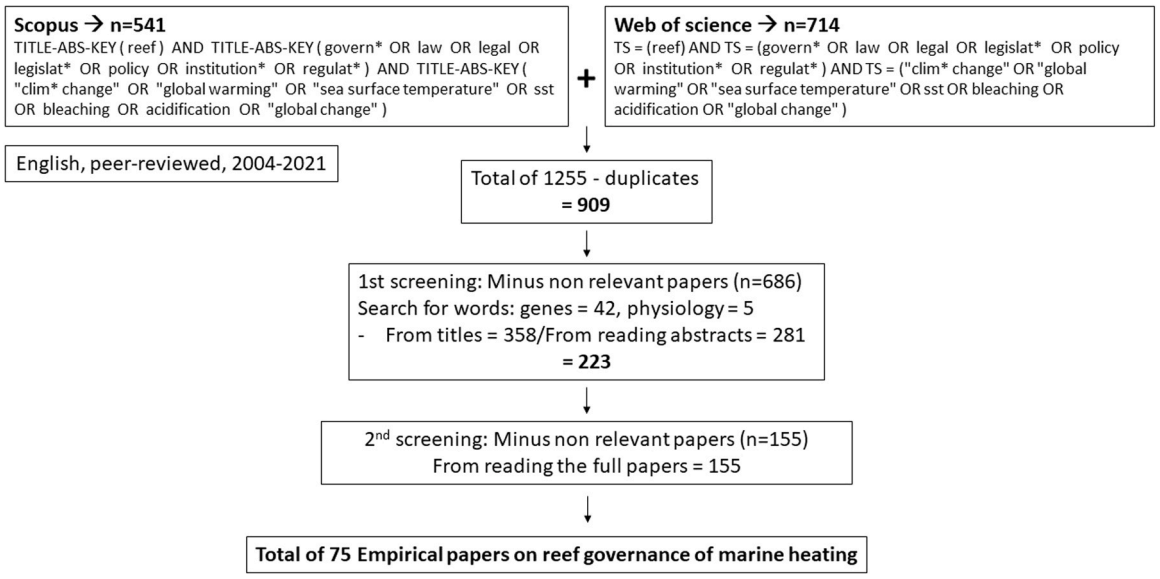

Fig. 1. Systematic review process.

climate. Of the studies addressing broader policy and governance challenges, we also found clear over-concentrations of research into identified barriers, which included but were not limited to:

(1) lack of regional cooperation – limited policy level cooperation and coordination among multiple states related to issues such as coral reef management, climate adaptation, fisheries and tourism [38];
(2) policy-science disconnection – the gap between the current scientific and technical understanding (both ecological and social) of coral reef management and actual policies and practices on ground [88,96];
(3) poor stakeholder awareness – limited understanding of marine heating issues by community members and other stakeholders [106,114,21]; and
(4) institutional path dependence – few to no triggers to create new pathways such as new institutional frameworks and instruments (regulatory, economic and educational), better policy coordination and more adaptive management [12,73].

Potential policy solutions canvassed ranged from improved planning and management, to improved organisational capacity, new institutions, and better governance (Fig. 2; Fig S1B). However, while many reef analysts acknowledged the need for such a broad range of solutions [39,10,95], most studies failed to explore that broad range of potential solutions. Indeed, most studies focused on a small subset of solutions, which we summarise here as more 'inclusive adaptation' and 'usable science' (Fig. 3). Noting that these terms encompass a variety of approaches, we employ 'inclusive adaptation' here as an umbrella term for any management measure involving local communities in iterative steps to assess and plan for marine climate risks and outcomes. We found that the aim of 'inclusive adaptation' solutions was overwhelmingly on planning to enhance resilience at the local level [11,113,60]. Usable science, similarly, refers to the multiscale efforts of biophysical scientists to ensure marine and coastal climate science is better integrated into government assessments, report cards and forecasts. We found that the aim of 'usable science' was mainly to enhance biophysical science 'usability' by a range of decision makers [36,54,58].

Notably, for both 'inclusive adaptation' and 'usable science', most studies presented these solutions as prescriptions rather than evidence-based. In other words, the majority of analyses were unclear about what actual policy solutions had been implemented and what had been effective. Furthermore, in many reef heating studies we found striking mismatches between the scale of the policy challenge identified in a particular study and the subsequent policy solution recommended (Fig. 4). This limited evidence-base and scalar mismatch between challenges and solutions reinforced our finding that the field is circling around a relatively narrow set of prescriptions and assumptions. Indeed, we found that while there has been a dramatic rise of scientific and policy interest in reef heating, dedicated interest in the policy solutions beyond 'inclusive adaptation' and 'usable science' have not yet emerged as important pathways forward. Our findings on the predominance of these solutions were supported by a cross-check with the themes for 2023's International Symposium on Effects of Climate Change on the World's Oceans (Norway, April), climate change streams at the Aquatic Systems Resilience and Recovery Meeting (Spain, June), and at the UN Adaptation Futures Conference (Montreal, October), many of which seemed to reproduce a narrow focus on local adaptation responses and better integration of science into policy.

4. Causes and consequences of science-policy lock-in

Science-policy lock-in, in environmental policy or climate policy, has been attributed to a range of different syndromes. These syndromes include path dependence [7], scale bias [31], disciplinary bias [23], sampling bias [51,82,1], excessive and singular reliance on community participation [107], mismatches between the scale of problems studied and proposed solutions [12], 'normal' science [86], and 'parachute' science [3,100].

The field of reef heating science and policy is just as susceptible to these syndromes as other fields. To begin with, the very understanding of reef heating was pioneered by biophysical scientists, with in-water ecological impacts attracting the most attention. As social impacts came to light, reef biologists began engaging with social scientists studying coastal communities adjacent to heavily studied ecological sites (e.g., [69]). Those communities and social scientists were heavily engaged in and influenced by community-based approaches [26] and commons and collective action theory [75]. Scientists working on larger scale governance issues (e.g., political scientists, macroeconomists) remained largely absent from studies of reef heating (although see recent works by [45,48]). As such, the challenges of reef heating were mostly studied as local community-based adaptation challenges. Interdisciplinary scientists also promoted the view that community-based adaptation and/or science-led solutions were solutions easily tractable

Table 1
Types of common reef heating policy challenges.

	Type	Policy challenge	Scale	Definition
1	Climate and other ecological impacts	Compound climate impacts	L-R	Direct environmental impacts of climate change at local scales (e.g., coral bleaching)
2		Ocean acidification	N-G	
3		Sea level rise	L-R	
4		Marine heating	L	
5		Compound non-climate impacts	L-R	Other environmental stressors which can exacerbate climate change impacts and marine degradation (e.g., pollution)
6		Generalised marine degradation	L	
7	Socio-economic risks of climate impacts	Impacts to fishery	L	Socio-economic impacts of climate change (e.g., on local fishery, economy, food security, tourism, human settlement patterns)
8		Tourism impacts	L-R	
9		Threats to food security	L	
10		Human migration	L-R	
11		Social-ecological transformations	L-R	
12		Economic impacts	L-R	
13		Community vulnerability	L	
14	Institutional and management challenges	Compound adaptation challenges	L-R	Management challenges with climate change adaptation, climate change mitigation and marine or coastal resilience actions
15		Institutional adaptation challenges	R	
16		Social adaptation challenges	L-R	
17		Ecological adaptation challenges	L-R	
18		Climate mitigation challenges	R-N	
19		Conservation management challenges	L-R	
20		Lack of opportunities for participation	L-R	
21		Poor management practices	R	
22	Broader governance and political challenges	Poor regional cooperation	N-G	Governance challenges with climate policy participation, cooperation, science uptake, political will and stakeholder perceptions
23		Policy science disconnect	N	
24		Lack of political will	N	
25		Unclear stakeholder perceptions	R	

Scale: L – Site, Community or Local government; R - Regional Ecosystem or Provincial, N- National, G – Transnational, Multinational or Global, M - Multi-scale

to the people directly affected: local communities and marine scientists [19,89]. Recommendations thus became limited to the prescriptions of these 'tractable' solutions, rather than based on analysis of the success or effectiveness of other solutions addressing marine heating, largely because that evidence did not yet exist [13,18].

However, as the field of reef heating policy matures, sharp attention to the consequences of science-policy lock-in is increasingly necessary. A continued narrow focus on inclusive adaptation and usable science as the primary solutions to marine heating is problematic for multiple reasons. First, one-size-fits-all approaches ignore how different socio-economic, cultural and demographic contexts might enable or inhibit uptake in particular locations. Second, the focus on local solutions places the burden of solutions onto vulnerable or relatively powerless groups, rather than on the parts of society responsible for causing the problem and with the most power to address it. Local communities, local

Table 2
Types of common reef heating policy solutions.

	Type	Policy solution	Scale	Definition
1	Better governance	Science-policy integration	M	Use of scientific data and analysis to inform, formulate and/or monitor policy; Vertical and horizontal integration of policies through inter-agency coordination; Deliberate governance across scales; Transnational/global coordination of policy/agencies, resource and information sharing, establishment of common objectives and standards
3		Better policy coordination	N	
4		Multi-scale governance	M	
5		Better regional cooperation	G	
6	New institutional arrangements	New institutions	N	New overarching laws, agencies or policies; New laws or procedures aiming to control/regulate social/economic actions; New financial and other economic incentives and disincentives established by law or policy; New policy or action plans promoting awareness and better cognition of reef or climate change; Legal or procedural changes impacting property relations
7		New regulation	N	
8		New economic instruments	N	
9		New educational instruments	N	
10				
11		Property rights reform	N	
12	Improved organisational capacity	Funding mechanisms	G	New funding allocations or restructuring existing funding allocations for reef/climate action; Programs to increase technical and management capacities of agencies to deal with reef/climate issues; Changes to existing laws, regulations and procedures
13		Agency capacity building	N	
14				
15		Legal and administrative reform	N	
16	Improved planning & management	Adaptive management	L	Any management measures involving iterative steps assessing risks and outcomes; Any management measures that are primarily based on community action; Improved policy participation (from informing/consultation to delegation/empowerment) and inclusion; Changes to current planning schemes; Carefully planned relocation of communities or ecosystems from and to reef areas; Formulation of testing/monitoring schemes, data management tools or models that can support reef/climate management
17		Community-based management	L	
18		Participation and inclusion	L	
19		Planning reform	N	
20		Planned relocation	G	
21		Developing technical tools	G	

Scale: L – Site, Community or Local government; R - Regional Ecosystem or Provincial, N- National, G – Transnational, Multinational or Global, M - Multi-scale

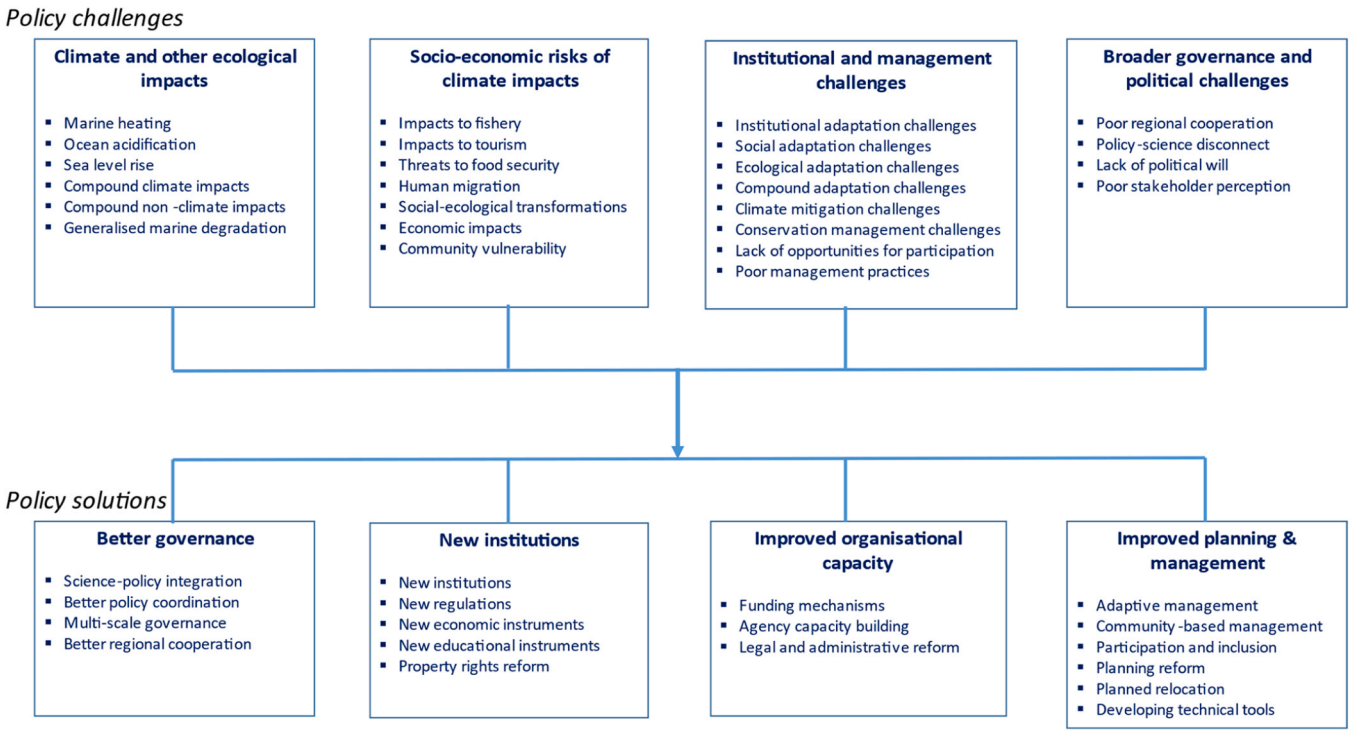

Fig. 2. Identified policy challenges and solutions to reef heating. The literature on reef heating (2004–21) identifies a suite of policy challenges that are not just ecological, but also socio-economic, institutional and political, and thus suggests a range of socio-economic, institutional and political solutions.

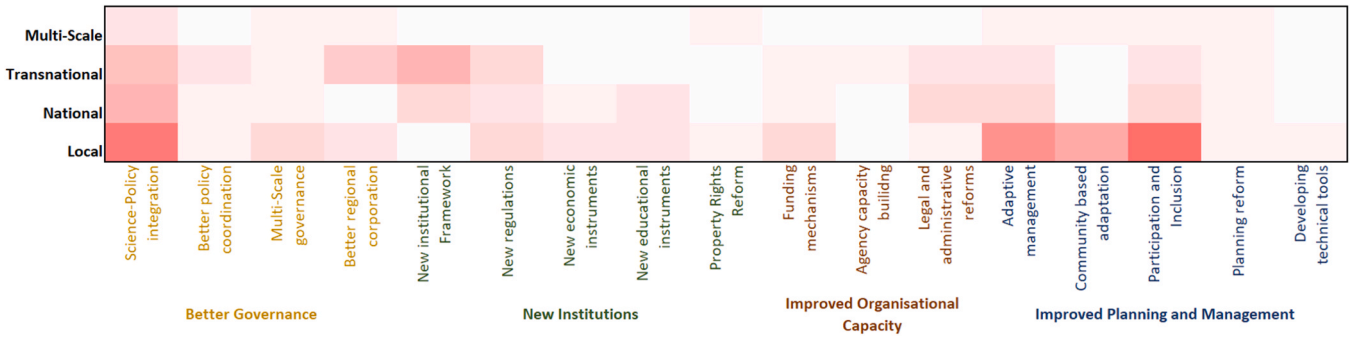

Fig. 3. Biases and gaps in identified science-policy solutions for reef heating. Strong bias toward 'inclusive adaptation' and 'usable science' in 75 research articles published 2004–2021 analysing solutions to reef heating. The red colour scale represents number of articles identifying a particular solution, with darker tones indicating a larger number of articles. Inclusive adaptation is an umbrella term for any management measure involving local communities in iterative steps to assess and plan for reef climate risks and outcomes. Usable science refers to multiscale efforts to ensure reef and coastal climate science is better integrated into government assessments, report cards and forecasts to enhance its 'usability' by a range of decision makers. While there has been a dramatic rise of scientific interest in the ecological and institutional effects of reef heating, scientific interest in the policy solutions beyond 'inclusive adaptation' and 'usable science' have not yet emerged as an important field in their own right.

managers, and indeed local marine scientists produce limited emissions and often have limited capacity; they therefore cannot be solely responsible for adaptation and mitigation [8]. Third, the dominance of a narrow set of solutions means alternative solutions at higher scales (e.g., adaptive capacity building of national and transnational institutions - [20,50] or property rights reforms - [90,91]) remain virtually ignored. Lock-in in reef heating science and policy deserves specific attention because obscuring more effective, efficient, and equitable solutions is maladaptive. Moreover, lock-in risks reproducing unchallenged assumptions about the appropriate level and organization of institutional responses to reef heating – with potential governance implications across all climate-impacted social-ecological systems [74].

5. Overcoming lock-in: future reef heating science and policy directions

In the past five years, with the severity of reef heating becoming more apparent and reef science increasingly multidisciplinary, important new policy questions and methods have emerged. Broader research focused on higher scales of governance is more prominent in response to the recognition of a growing global connectivity and the global origin of local-scale threats [32]. Increasingly severe back-to-back coral bleaching events have also triggered a paradigm change in reef social science, which now recognises that institutional factors fundamentally shape our ability to design adaptive and transformative interventions across a range of scales [75]. Key to such advancement is a transdisciplinary approach, engaging researchers from across different disciplines and non-academic stakeholders to co-produce knowledge and pursue

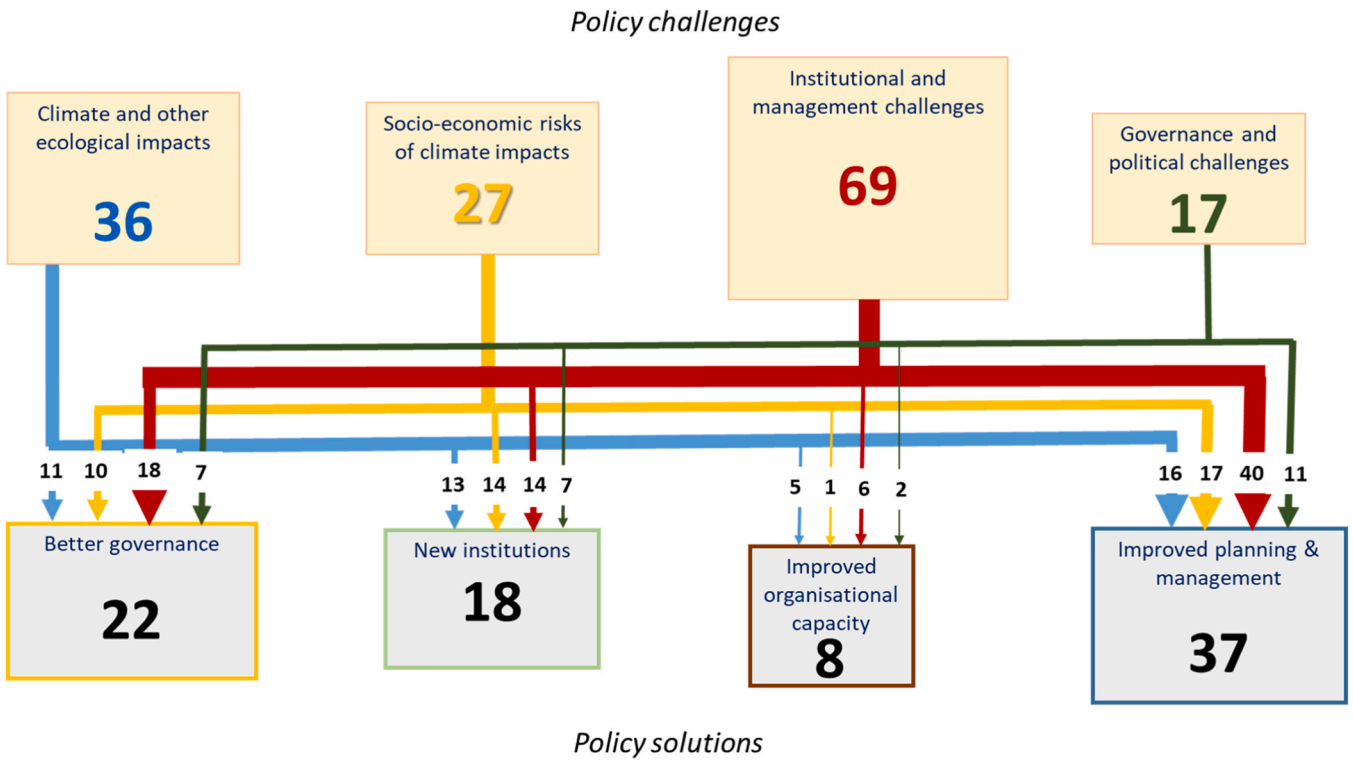

Fig. 4. Problem-solution mismatch and normativity in identified policy solutions to reef heating (n = 75 papers). There are clear mismatches in logic between the challenges identified and the proposed solutions. The relationship between issues and intervention identified are shown, where the size of the boxes and the numbers within represent the number of papers citing key challenges (yellow) or key solutions (grey). Arrow and line width represent the number of papers identifying a connection between each challenge and solution.

actionable solutions [105,24,72]. However, despite the raft of oceans strategies in 2024, there is surprisingly little work drawing this new research together into a comprehensive agenda applicable to the governance of reef heating. Drawing on our systematic review, we identify four promising research directions that could prove critical to overcoming lock-in of science and policy responses to reef heating (Fig. 5). Acknowledging that many climate and environment challenges are wicked and open-ended and can never be fully "solved" [111,57], our aim is to provide researchers, practitioners, policymakers and funders with ideas for how inclusive adaptation and usable science can be better supported, as well as to provide additional new ideas for targeted reef science, investment and policy action beyond inclusive adaptation

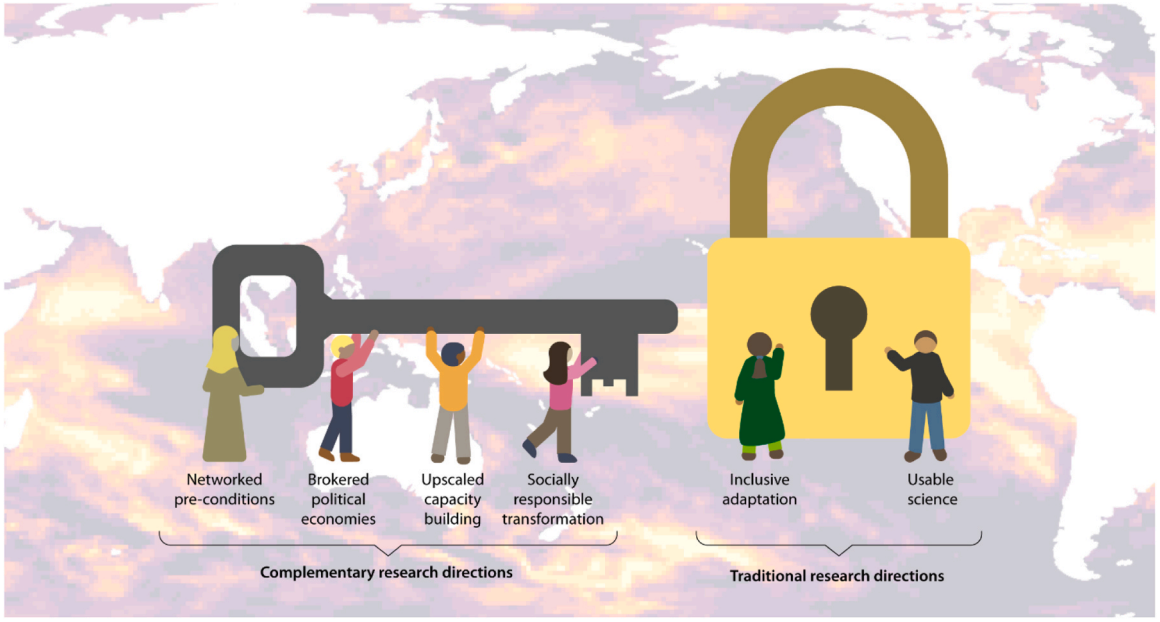

Fig. 5. Overcoming lock-in of science-policy responses to reef heating. Science-policy responses to reef heating are locked-in to a critical yet narrow range of solutions recommending more 'inclusive adaptation' and more 'usable' science. Drawing on our review, we identify new directions to both enable and expand the existing solution space.

and usable science.

5.1. Socially responsible transformation

Many novel interventions in reef heating (e.g., mangrove restoration, cloud brightening, coral bioengineering) are now being funded, researched and implemented [28,80,98]. Effective oversight of these interventions requires transformations in reef policy [70,101]. In the past two decades, marine policy scientists have made significant progress conceptualising and analysing such a transformative process whereby solutions move from an incremental improvement of established strategies to adjustment for evolving conditions, and finally to the implementation of fundamentally new solutions [73,84]. However, understanding of transformation in reef heating policy has remained hampered by two major limitations. The first is the theoretical assumption that higher-order learning is possible, when in fact there remains scarce evidence of policy responses to reef heating moving beyond incrementalism in impacted reef systems [12]. The second key limitation is the recurring focus on stakeholder-based decision-making [84] when accumulating evidence suggests that even when local collaborative structures are in place, policy learning is heavily influenced by other drivers [110,73,94].

Indeed, the rise of reef credits, Global North philanthropism, and large-scale adaptation and restoration programs highlights how reef heating policy is no longer the sole province of communities nor of the state. Government policymakers and other actors must now negotiate and navigate amongst radically different interests in intervening in marine ecosystems, including those of marine funders and entrepreneurs, citizen-led start-ups, and advanced scientific and industrial innovators [16,59,87]. In making intervention decisions, these new actors are increasingly influencing how reef spaces and resources are used, managed and occupied. Understanding the roles these different actors perform at different scales in responding to reef heating, the outcomes of their actions, and whether they are considered fair and legitimate by various stakeholders has the potential to offer critical insights for more effective, equitable and legitimate solutions and to prevent maladaptation [14,74]. Recent research on marine conservation in Fiji, for example, has revealed misalignment between the distributional justice principles preferred by local actors and those commonly embedded in Global North conservation tools and practice [47]. Other research has highlighted how ethics, morality and legitimacy are both embedded across and challenged by institutions such as climate markets, climate philanthropism, and large-scale science programs [108,61,62,64].

5.2. Upscaled capacity building

Many reef agencies simply do not have the organisational capacity to respond effectively to marine heating. While development agencies, non-governmental organisations, philanthropists, and governments are now significantly investing in reef systems and associated communities, many of these investments still focus on short-term measurables and attributes - such as marine protected area (MPA) coverage, or legal and administrative improvements to the capacity of marine managers to implement MPAs. National and sub-national agencies, along with local NGOs and communities, are often left with the realities of deeper, slower and messier changes which they may or may not be equipped to handle. For example, the impacts of climate change, the rise of bioengineering and blue carbon markets, and the realisation of 'climate coloniality' together raise serious questions about displacement, rights and tenure that marine organisations are often critically underprepared to address [102,92].

Fortunately, new frameworks are emerging that look beyond stop-start funding and embrace the more intangible, slower and complex aspects of organisational and institutional capacity building. These broader views of capacity building involve assets, flexibility, social organisation, learning, socio-cognitive constructs, and agency [25,79]. While mainly tested at the community level, reef researchers are now exploring the potential for these broader frameworks to be usefully applied at higher scales to inform larger-scale and indeed multi-scale investment into capacity-building (e.g., [68,5,99]). The Packard Foundation's multi-decadal "Western Pacific Program" (1998–2020), while not focused on reef heating, was an excellent example of institutional capacity building at scale through long-term grassroots funding, NGO capacity-building, and community empowerment that placed equity in marine governance at the core [16,37]. More recently, the 'Niue Ocean Wide' initiative involves an innovative financing and sponsorship mechanism managed by the 'Niue Ocean Wide' Trust—a partnership between the Government of Niue and local nonprofit, Tofia Niue [59,81]. UNESCO's ocean literacy agenda, by contrast, is designed to globally diffuse higher-level understanding of connections to, and attitudes and behaviours towards climate impacted coral reefs [65,93]. New global studies of best practices and 'enablers' such as the Bright Spots [27] and 50 reefs [15] projects could also be used to inform national and international decision-making beyond local protected area programs attempting to build marine resilience. Such sampling of successful policies and practices is also important to shift the weight of evidence away from vulnerabilities, deficits and barriers. Evidence of best practices, enablers and 'bright spots' [27] can help understand what works as opposed to what does not, provide a larger pool of evidence about success from which others can learn, inspire hopeful change and serve as an antidote to despair [41].

5.3. Networked pre-conditions

New analyses demonstrate how social-ecological connectivity comprises a key pre-condition that can support (or undermine) institutional responses to reef heating. For example, specific connections between people, institutions, and reefs (i.e., social–ecological ties) can support responses by enabling learning and the internalisation of ecological feedbacks [6]. Social-ecological network approaches offer a promising way forward for understanding and managing these connections, allowing researchers and policymakers to identify and support different patterns of interaction among and between people and ecosystems that can enable responses at different scales [17]. These approaches can provide a more complete picture of the multilevel networked structure and function of reefs and reef peoples as multiscale social-ecological systems [33].

Because quantitative analyses of structure and function involve a necessary reductionism that may miss other fundamental properties of complex systems, such as context and embeddedness, reef network analysts are now combining quantitative measurement of networks with qualitative and discursive methods, such as expert assessment and ethnographic and interpretive techniques [112]. Some researchers are analysing temporal trends in reef governance networks to understand how institutional actors can coordinate responses to marine heating across scales [76,34]. Other researchers are investigating fish value chains and trade networks to understand how people can adapt the way they market and value marine resources in response to heating shocks [42]. Certain types of connectivity — e.g., clustered or fragmented networks - can stall or impede large-scale responses [4], which can cause mental blocks or create an 'us-them' attitude. Under different conditions, responsive behaviour can be reinforced through processes of social influence and contagion in networks, and through the formation of new social and institutional connections [6]. As waters warm, there is much to be gained from understanding how social, institutional and ecological connectivity can support transformative policy solutions.

5.4. Brokered political-economies

Addressing the risks and impacts of reef heating requires attending to climate mitigation, climate adaptation and climate resilience. These are vastly different science-policy challenges requiring very different types

of science-policy solutions to address them effectively. Reef researchers are therefore increasingly working beyond the coral reef field to take advantage of the many lessons available within a more general political economy framework as highlighted in the IPCC assessments and by marine policy experts more broadly [115,49,85]. Within those frameworks, there is considerable scope for more novel solutions—e.g., post-growth marine policies, taxes and future funds, and interlocking approaches to restore marine ecosystems and marine tenure— to help alleviate some of the causes and effects of marine heating (e.g., [90,8,74]).

Because many of these novel solutions are unproven and require trials and experiments to test their feasibility and effectiveness, marine policy scientists are beginning to work on larger scale governance issues through ambitious research designs that include stakeholders from diverse sectors, scales and places and are in turn driving new forms of collaboration, empowerment, power brokerage and collective action (e.g. see [16,45,85]). Such proof-of-concept research is far from the norm in most disciplines engaged in research on marine heating, and challenging because it entails research that is: risky in that it may fail; expensive and complicated in terms of engagement; and of a longer duration than most projects because it takes time to properly monitor and evaluate novel solutions. These more novel and impactful forms of research are also a challenge to research funders and users because they entail bigger costs, longer time scales, and, in many cases a willingness to take big political risks. However, seeing and understanding reef heating as situated within a broader political-economic system is beginning to offer a much deeper set of insights into what can be changed, why efforts to achieve more effective governance can be so challenging, and what kinds of new solutions are possible [74,75].

6. Conclusion: an expanded mission for reef science-policy leaders

As the reality of climate change becomes more pronounced, and as investment in marine science and policy increases, the continuing emphasis on locally inclusive adaptation and usable science is beginning to be supplemented with a broader range of approaches. The substantive directions we outline above are shifting science and policy to better grasp the complexity of marine heating and, more importantly, to ensure proposed solutions have greater impact at all relevant scales. Fortunately, a new generation of researchers are rising to meet this challenge and are advancing science and policy in novel ways, with a notable commitment to co-production and impact. Co-production, in particular, is critical to ensuring new solutions are tailored to different socio-cultural, economic, and demographic contexts. Importantly, new co-produced approaches are not limited to local communities, local managers, and local marine scientists, but directly engage other parts of society, including powerful actors responsible for causing and/or solving the problem of marine heating. As marine systems continue to heat in the decades to come, funders, governments and scientists would do well to support such tailored and multiscale science and policy to unlock a broader range of solutions for our warming coral reefs.

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CRediT authorship contribution statement

Tiffany H Morrison: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Missaka Hettiarachchi:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Pip Cohen:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Josh Cinner:** Writing – review & editing, Writing – original draft, Funding acquisition. **Jon Barnett:** Writing – review & editing, Writing – original draft, Funding acquisition. **Georgina G. Gurney:** Writing – review & editing, Writing – original draft, Funding acquisition. **Jacqueline Lau:** Writing – review & editing, Writing – original draft. **Michele L. Barnes:** Writing – review & editing, Writing – original draft, Funding acquisition.

Declaration of Competing Interest

The authors have no competing interests to declare.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

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References

[1] C. Adams, T. Ide, J. Barnett, A. Detges, Sampling bias in climate–conflict research, Nat. Clim. Chang. 8 (3) (2018) 200–203.
[2] W.N. Adger, J. Barnett, S. Heath, S. Jarillo, Climate change affects multiple dimensions of well-being through impacts, information and policy responses, Nat. Hum. Behav. (2022) 1–9.
[3] G.N. Ahmadia, S.H. Cheng, D.A. Andradi-Brown, S.K. Baez, M.D. Barnes, N. J. Bennett, S.J. Campbell, E.S. Darling, Estradivari, D. Gill, E. Gress, Limited progress in improving gender and geographic representation in coral reef science, Front. Mar. Sci. 8 (2021) 731037.
[4] M.L. Barnes, Ö. Bodin, A.M. Guerrero, R.R. McAllister, S.M. Alexander, G. Robins, The social structural foundations of adaptation and transformation in social–ecological systems, Ecol. Soc. 22 (4) (2017).
[5] M.L. Barnes, A. Datta, S. Morris, I. Zethoven, Navigating climate crises in the Great Barrier Reef, Glob. Environ. Change 74 (2022) 102494.
[6] M.L. Barnes, P. Wang, J.E. Cinner, N.A. Graham, A.M. Guerrero, L. Jasny, J. Lau, S.R. Sutcliffe, J. Zamborain-Mason, Social determinants of adaptive and transformative responses to climate change, Nat. Clim. Change 10 (9) (2020) 823–828.
[7] J. Barnett, L.S. Evans, C. Gross, A.S. Kiem, R.T. Kingsford, J.P. Palutikof, C. M. Pickering, S.G. Smithers, From barriers to limits to climate change adaptation: path dependency and the speed of change, Ecol. Soc. 20 (3) (2015) 5.
[8] J. Barnett, S. Jarillo, S.E. Swearer, C.E. Lovelock, A. Pomeroy, T. Konlechner, E. Waters, R.L. Morris, R. Lowe, Nature-based solutions for atoll habitability, Philos. Trans. R. Soc. B 377 (1854) (2022) 20210124.
[9] M.W. Beck, I.J. Losada, P. Menéndez, B.G. Reguero, P. Díaz-Simal, F. Fernández, The global flood protection savings provided by coral reefs, Nat. Commun. 9 (1) (2018) 2186.
[10] M. Beger, J. McGowan, E. Treml, et al., Integrating regional conservation priorities for multiple objectives into national policy, Nat. Commun. 6 (2015) 8208.
[11] J.D. Bell, A. Cisneros-Montemayor, Q. Hanich, J.E. Johnson, P. Lehodey, B. R. Moore, M.S. Pratchett, G. Reygondeau, I. Senina, J. Virdin, C.C.C. Wabnitz, Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands, Mar. Policy 88 (2018) 303–314.
[12] D.R. Bellwood, M.S. Pratchett, T.H. Morrison, et al., Coral reef conservation in the Anthropocene: confronting spatial mismatches and prioritizing functions, Biol. Conserv. (2019), https://doi.org/10.1016/j.biocon.2019.05.056.

[13] L. Berrang-Ford, A.R. Siders, A. Lesnikowski, A.P. Fischer, M.W. Callaghan, N. R. Haddaway, K.J. Mach, M. Araos, M.A.R. Shah, M. Wannewitz, D. Doshi, A systematic global stocktake of evidence on human adaptation to climate change, Nat. Clim. Change 11 (11) (2021) 989–1000.

[14] M.M. Betsill, A. Enrici, E. Le Cornu, R.L. Gruby, Philanthropic foundations as agents of environmental governance: a research agenda, Environ. Polit. 31 (4) (2022) 684–705.

[15] H.L. Beyer, E.V. Kennedy, M. Beger, C.A. Chen, J.E. Cinner, E.S. Darling, C. M. Eakin, R.D. Gates, S.F. Heron, N. Knowlton, D.O. Obura, Risk-sensitive planning for conserving coral reefs under rapid climate change, Conserv. Lett. 11 (6) (2018) e12587.

[16] J.E. Blackwatters, M. Betsill, A. Enrici, E. Le Cornu, X. Basurto, R.L. Gruby, More than funders: the roles of philanthropic foundations in marine conservation governance, Conserv. Sci. Pract. (2022) e12829.

[17] Örjan Bodin, Steven M. Alexander, Jacopo Baggio, Michele L. Barnes, Ramiro Berardo, Graeme S. Cumming, Laura E. Dee, et al., Improving network approaches to the study of complex social–ecological interdependencies, Nat. Sustain. 2 (7) (2019) 551–559.

[18] W.R. Brooks, M.E. Rudd, S.H. Cheng, B.R. Silliman, D.A. Gill, G.N. Ahmadia, D. A. Andradi-Brown, L. Glew, L.M. Campbell, Social and ecological outcomes of conservation interventions in tropical coastal marine ecosystems: a systematic map protocol, Environ. Evid. 9.1 (2020).

[19] K. Brown, W.N. Adger, J.E. Cinner, Moving climate change beyond the tragedy of the commons, Glob. Environ. Change (2019).

[20] J.R.A. Butler, S. Busilacchi, T. Skewes, How resilient is the Torres Strait Treaty (Australia and Papua New Guinea) to global change? A fisheries governance perspective, Environ. Sci. Policy 91 (2019) 10.

[21] C. Camargo, J.H. Maldonado, E. Alvarado, et al., Community involvement in management for maintaining coral reef resilience and biodiversity in southern Caribbean marine protected areas, Biodivers. Conserv 18 (2009) 935–956.

[22] D.W. Cash, W.N. Adger, F. Berkes, P. Garden, L. Lebel, P. Olsson, L. Pritchard, O. Young, Scale and cross-scale dynamics: governance and information in a multilevel world, Ecol. Soc. 11 (2) (2006).

[23] N. Castree, W.M. Adams, J. Barry, D. Brockington, B. Büscher, E. Corbera, D. Demeritt, R. Duffy, U. Felt, K. Neves, P. Newell, Changing the intellectual climate, Nat. Clim. Change 4 (9) (2014) 763–768.

[24] J.M. Chambers, C. Wyborn, M.E. Ryan, R.S. Reid, M. Riechers, A. Serban, N. J. Bennett, C. Cvitanovic, M.E. Fernández-Giménez, K.A. Galvin, Six modes of co-production for sustainability, Nat. Sustain. 4 (2021) 983–996.

[25] J.E. Cinner, W.N. Adger, E.H. Allison, M.L. Barnes, K. Brown, P.J. Cohen, S. Gelcich, C.C. Hicks, T.P. Hughes, J. Lau, N.A. Marshall, T.H. Morrison, Building adaptive capacity to climate change in tropical coastal communities, Nat. Clim. Change 8 (2) (2018) 117–123.

[26] J.E. Cinner, C. Huchery, E.S. Darling, A.T. Humphries, N.A. Graham, C.C. Hicks, N. Marshall, T.R. McClanahan, Evaluating social and ecological vulnerability of coral reef fisheries to climate change, PloS One 8 (9) (2013) e74321.

[27] J.E. Cinner, C. Huchery, M.A. MacNeil, N.A. Graham, T.R. McClanahan, J. Maina, E. Maire, J.N. Kittinger, C.C. Hicks, C. Mora, E.H. Allison, Bright spots among the world's coral reefs, Nature *535* (7612) (2016) 416–419.

[28] M.D.P. Costa, R. Gorddard, P. Fidelman, K.J. Helmstedt, K.R.N. Anthony, K. A. Wilson, H.L. Beyer, Linking social and biophysical systems to inform long-term, strategic management of coral reefs, Pac. Conserv. Biol. 27 (2021) 126–132, https://doi.org/10.1071/PC20002.

[29] A. Cruz-Trinidad, P.M. Aliño, R.C. Geronimo, R.B. Cabral, Linking food security with coral reefs and fisheries in the coral triangle, Coast. Manag. 42 (2) (2014) 160–182, https://doi.org/10.1080/08920753.2014.877761.

[30] S.C. Cuevas, A. Peterson, C. Robinson, T.H. Morrison, Institutional capacity for long-term climate change adaptation: evidence from land use planning in Albay, Philippines, Reg. Environ. Change 16 (2016) 2045–2058.

[31] G.S. Cumming, A review of social dilemmas and social-ecological traps in conservation and natural resource management, Conserv. Lett. 11 (1) (2018) e12376.

[32] G.S. Cumming, M. Adamska, M.L. Barnes, J. Barnett, D.R. Bellwood, J.E. Cinner, P. Cohen, J. Donelson, K. Fabricius, R.Q. Grafton, A. Grech, G.G. Gurney, O. Hoegh-Guldberg, A.S. Hoey, M.O. Hoogenboom, J. Lau, C. Lovelock, R. Lowe, D. Miller, T.H. Morrison, P.J. Mumby, M. Nakata, J.M. Pandolfi, G.D. Peterson, M. Pratchett, T. Ravasi, C. Riginos, J.L. Rummer, B. Schaffelke, T. Wernber, S. Wilson, Research priorities for the sustainability of coral-rich western Pacific seascapes, Reg. Environ. Change (2023) (In Press.).

[33] G.S. Cumming, T.H. Morrison, T.P. Hughes, New directions for understanding the spatial resilience of social–ecological systems, Ecosystems 20 (2017) 649–664.

[34] A. Datta, M.L. Barnes, B. Chaffin, T. Floyd, T. Morrison, S. Sutcliffe, Big events, little change: Extreme climatic events have no region-wide effect on Great Barrier Reef governance, J Environ. Manage. 320 (2022) 115809.

[35] S. Donner, D. Potere, The inequity of the global threat to coral reefs, Bioscience 57 (2007) 214–215.

[36] P.K. Dunstan, B.R. Moore, J.D. Bell, N.J. Holbrook, E.C.J. Oliver, J. Risbey, S. D. Foster, Q. Hanich, A.J. Hobday, N.J. Bennett, How can climate predictions improve sustainability of coastal fisheries in Pacific Small-Island Developing States? Mar. Policy 88 (2018) 2018.

[37] A. Enrici, R.L. Gruby, M.M. Betsill, E. Le Cornu, J.E. Blackwatters, X. Basurto, H. Govan, T. Holm, S.D. Jupiter, S. Mangubhai, Who's setting the agenda? Philanthropic donor influence in marine conservation, Ecol. Soc. 28 (3) (2023).

[38] S. Foale, D. Adhuri, P. Aliño, E.H. Allison, N. Andrew, P. Cohen, L. Evans, M. Fabinyi, P. Fidelman, Food security and the Coral Triangle Initiative, in: C. Gregory, N. Stacey, J. Tanzer, N. Weeratunge (Eds.), Mar. Policy 38 (2013) 174–183.

[39] J. Forster, I.R. Lake, A.R. Watkinson, J.A. Gill, Marine biodiversity in the Caribbean UK overseas territories: Perceived threats and constraints to environmental management, Mar. Policy 35 (5) (2011) 647–657.

[40] T.L. Frölicher, E.M. Fischer, N. Gruber, Marine heatwaves under global warming, Nature 560 (7718) (2018) 360–364.

[41] N. Geiger, J.K. Swim, K. Gasper, J. Fraser, K. Flinner, How do I feel when I think about taking action? Hope and boredom, not anxiety and helplessness, predict intentions to take climate action, J. Environ. Psychol. 76 (2021) 101649.

[42] Blanca González-Mon, Örjan Bodin, Beatrice Crona, Mateja Nenadovic, Xavier Basurto, Small-scale fish buyers' trade networks reveal diverse actor types and differential adaptive capacities, Ecol. Econ. 164 (2019) 106338.

[43] H.S. Grantham, E. Mcleod, A. Brooks, et al., Ecosystem-based adaptation in marine ecosystems of tropical Oceania in response to climate change, Pac. Conserv. Biol. Vol. 17 (2011) 241–258.

[44] L. Groen, M. Alexander, J.P. King, N.W. Jager, D. Huitema, Re-examining policy stability in climate adaptation through a lock-in perspective, J. Eur. Public Policy 30 (3) (2023) 488–512.

[45] R.L. Gruby, A. Enrici, M. Betsill, E. Le Cornu, X. Basurto, R. Co-Designers, Opening the black box of conservation philanthropy: A co-produced research agenda on private foundations in marine conservation, Mar. Policy 132 (2021) 104645.

[46] G. Gurney, J. Blythe, H. Adams, W. Adger, M. Curnock, L. Faulkner, T. James, N. A. Marshall, Redefining community based on place attachment in a connected world, Proc. Natl. Acad. Sci. 114 (38) (2017) 10077–10082.

[47] G. Gurney, S. Mangubhai, M. Fox, M. Kim, A. Agrawal, Equity in environmental governance: perceived fairness of distributional justice principles in co-management of marine commons in Fiji, Environ. Sci. Policy 124 (2021) 23–32.

[48] J. Hamilton, X. Basurto, H. Smith, J. Virdin, How does the World Bank shape global environmental governance agendas for coasts? 50 years of small-scale fisheries aid reveals paradigm shifts over time, Glob. Environ. Change 68 (2021) 102246.

[49] Q. Hanich, C.C.C. Wabnitz, Y. Ota, M. Amos, C. Donato-Hunt, A. Hunt, Small-scale fisheries under climate change in the Pacific Islands region, Mar. Policy 88 (2018) 2018.

[50] E.R. Harrould-Kolieb, The UN Convention on the Law of the Sea: a governing framework for ocean acidification? Rev. Eur. Comp. Int. Environ. Law 29 (2) (2020).

[51] C.S. Hendrix, The streetlight effect in climate change research on Africa, Glob. Environ. Change 43 (2017) 137–147.

[52] S.F. Heron, R. van Hooidonk, J. Maynard, K. Anderson, J.C. Day, E. Geiger, O. Hoegh-Guldberg, T. Hughes, P. Marshall, D. Obura, C.M. Eakin. Impacts of Climate Change on World Heritage Coral Reefs: Update to the First Global Scientific Assessment, UNESCO World Heritage Centre, Paris, 2018.

[53] C. Hicks, J. Cinner, Social, institutional, and knowledge mechanisms mediate diverse ecosystem service benefits from coral reefs, PNAS (2014).

[54] N.J. Holbrook, A. Sen Gupta, E.C. Oliver, A.J. Hobday, J.A. Benthuysen, H. A. Scannell, D.A. Smale, T. Wernberg, Keeping pace with marine heatwaves, Nat. Rev. Earth Environ. 1 (9) (2020) 482–493.

[55] T.P. Hughes, K.D. Anderson, S.R. Connolly, S.F. Heron, J.T. Kerry, J.M. Lough, A. H. Baird, J.K. Baum, M.L. Berumen, T.C. Bridge, D.C. Claar, Spatial and temporal patterns of mass bleaching of corals in the Anthropocene, Science 359 (6371) (2018) 80–83.

[56] T.P. Hughes, M.L. Barnes, D.R. Bellwood, J.E. Cinner, G.S. Cumming, J. B. Jackson, J. Kleypas, I.A. van de Leemput, J.M. Lough, T.H. Morrison, S. R. Palumbi, Coral reefs in the Anthropocene, Nature 546 (7656) (2017) 82–90.

[57] IPCC Climate Change 2022, in: H.-O. Pörtner, et al. (Eds.), Impacts, Adaptation, and Vulnerability, Univ. Cambridge, 2022.

[58] M.G. Jacox, M.A. Alexander, D. Amaya, E. Becker, S.J. Bograd, S. Brodie, E. L. Hazen, M. Pozo Buil, D. Tommasi, Global seasonal forecasts of marine heatwaves, Nature 604 (7906) (2022) 486–490.

[59] J.N. Kittinger, R.D. Rotjan, Q. Hanich, B. Pasisi, C. Rambourg, Balancing protection and production in ocean conservation, npj Ocean Sustain. 3 (1) (2024) 24.

[60] V.W. Lam, E.H. Allison, J.D. Bell, J. Blythe, W.W. Cheung, T.L. Frölicher, M. A. Gasalla, U.R. Sumaila, Climate change, tropical fisheries and prospects for sustainable development, Nat. Rev. Earth Environ. 1 (9) (2020) 440–454.

[61] J. Lau, et al., Morals and climate decision-making: insights from social and behavioural sciences, in: Current Opinion in Environmental Sustainability, 52, Elsevier B.V., 2021, pp. 27–35, https://doi.org/10.1016/j.cosust.2021.06.005.

[62] J. Lau, G. Gurney, J. Cinner, Environmental justice in coastal systems: Perspectives from communities confronting change, Glob. Environ. Change 66 (2021) 102208.

[63] J. Lau, C. Hicks, G. Gurney, J. Cinner, Disaggregating ecosystem service values and priorities by wealth, age, and education, Ecosyst. Serv. 21 (2018) 91–98.

[64] J. Lau, S. Sutcliffe, M. Barnes, E. Mbaru, I. Muly, N. Muthiga, S. Wanyonyi, J. E. Cinner, COVID-19 impacts on coastal communities in Kenya, Mar. Policy 134 (2021) 104803.

[65] S. Lawless, A.M. Song, P.J. Cohen, T.H. Morrison, Rights, equity and justice: A diagnostic for social meta-norm diffusion in environmental governance, Earth Syst. Gov. 6 (2020) 100052.

[66] Eva Maire, et al., How accessible are coral reefs to people? A global assessment based on travel time, Ecol. Lett. 19 (4) (2016) 351–360.

[67] S.S. Mamauag, Porfirio M. Aliño, Renmar Jun S. Martinez, Richard N. Muallil, Maria Victoria A. Doctor, Emerlinda C. Dizon, Rollan C. Geronimo, Fleurdeliz

M. Panga, Reniel B. Cabral, A framework for vulnerability assessment of coastal fisheries ecosystems to climate change—Tool for understanding resilience of fisheries (VA–TURF), Fish. Res. 147 (2013) 381–393.
[68] J.G. Mason, J.G. Eurich, J.D. Lau, W. Battista, C.M. Free, K.E. Mills, K. Tokunaga, L.Z. Zhao, M. Dickey-Collas, M. Valle, G.T. Pecl, J.E. Cinner, T.R. McClanahan, E. H. Allison, W.R. Friedman, C. Silva, E. Yáñez, M.Á. Barbieri, K.M. Kleisner, Attributes of climate resilience in fisheries: from theory to practice, Fish Fish 23 (2022) 522–544.
[69] T.R. McClanahan, J.E. Cinner, J. Maina, N.A.J. Graham, T.M. Daw, S.M. Stead, A. Wamukota, K. Brown, M. Ateweberhan, V. Venus, N.V.C. Polunin, Conservation action in a changing climate, Conserv. Lett. 1 (2) (2008) 53–59.
[70] J. McDonald, J. McGee, K. Brent, W. Burns, Governing geoengineering research for the Great Barrier Reef, Clim. Policy 19 (2019) 7.
[71] R. McLean, P. Kench, Destruction or persistence of coral atoll islands in the face of 20th and 21st century sea-level rise? WIREs Clim. Change 6 (2015) 445–463.
[72] A.M. Meadow, D.B. Ferguson, Z. Guido, A. Horangic, G. Owen, T. Wall, Moving toward the deliberate coproduction of climate science knowledge, Weather Clim. Soc. 7 (2015) 179–191, https://doi.org/10.1175/WCAS-D-14-00050.1.
[73] T.H. Morrison, Evolving polycentric governance of the Great Barrier Reef, PNAS 114 (15) (2017) E3013–E3021, https://doi.org/10.1073/pnas.1620830114.
[74] T.H. Morrison, W.N. Adger, A. Agrawal, K. Brown, M.J. Hornsey, T.P. Hughes, M. Jain, M.C. Lemos, L.H. McHugh, S. O'Neill, D. Van Berkel, Radical interventions for climate-impacted systems, Nat. Clim. Change (2022) 1–7.
[75] T.H. Morrison, N. Adger, J. Barnett, K. Brown, H. Possingham, T. Hughes, Advancing coral reef governance into the anthropocene, One Earth 2 (1) (2020).
[76] T.H. Morrison, Ö. Bodin, G.S. Cumming, M. Lubell, R. Seppelt, T. Seppelt, C. M. Weible, Building blocks of polycentric governance, Policy Stud. J. (2023).
[77] T.H. Morrison, T.P. Hughes, W.N. Adger, K. Brown, J. Barnett, M.C. Lemos, D. Huitema, C. Huchery, T. Chaigneau, R. Turner, M. Hettiarachchi, Save reefs to rescue all ecosystems, Nature 573 (2019) 333–336.
[78] N.A. Muthiga, Evaluating the effectiveness of management of the Malindi–Watamu marine protected area complex in Kenya. 2009, Ocean Coast. Manag. 52 (8) (2009) 417–423, https://doi.org/10.1016/j.ocecoaman.2009.06.001.
[79] J. Nalau, B. Verrall, Mapping the evolution and current trends in climate change adaptation science, Clim. Risk Manag. 32 (2021) 100290.
[80] NASEM, A research review of interventions to increase the persistence and resilience of coral reefs, National Academies of Sciences, Engineering, and Medicine, Washington DC, 2019.
[81] Niue Ocean Wide, (2024).⟨https://www.niueoceanwide.com/⟩ (accessed June 13, 2024).
[82] P.D. Nunn, W. Aalbersberg, S. Lata, M. Gwilliam, Beyond the core: community governance for climate-change adaptation in peripheral parts of Pacific Island Countries, Reg. Environ. Change *14* (1) (2014) 221–235.
[83] E.C. Oliver, M.G. Donat, M.T. Burrows, P.J. Moore, D.A. Smale, L.V. Alexander, J. A. Benthuysen, M. Feng, A. Sen Gupta, A.J. Hobday, N.J. Holbrook, Longer and more frequent marine heatwaves over the past century, Nat. Commun. 9 (1) (2018) 1–12.
[84] P. Olsson, C. Folke, T.P. Hughes, Navigating the transition to ecosystem-based management of the Great Barrier Reef, Australia, Proc. Natl. Acad. Sci. 105 (28) (2008) 9489–9494.
[85] H. Österblom, J. Bebbington, R. Blasiak, M. Sobkowiak, C. Folke, Transnational corporations, biosphere stewardship, and sustainable futures, Annu. Rev. Environ. Resour. 47 (2022) 609–635.
[86] D. Pauly, Beyond our original horizons: the tropicalization of Beverton and Holt, Rev. Fish. Biol. Fish. 8 (1998) 307–334.
[87] Pecl, et al., Autonomous adaptation to climate-driven change in marine biodiversity in a global marine hotspot, Ambio 48 (2019) 1498–1515.
[88] L. Pendleton, A. Comte, C. Langdon, J.A. Ekstrom, S.R. Cooley, L. Suatoni, et al., Coral Reefs and People in a High-CO2 World: where can science make a difference to people? PLoS ONE 11 (11) (2016) e0164699.
[89] H.P. Possingham, M. Bode, C.J. Klein, Optimal conservation outcomes require both restoration and protection, PLOS Biol. 13 (2015).
[90] S. Pradhan, P. Cohen, 2023(In press)Brief for Funders; Pathways toward Equitable Climate Resilience, Sustainable Fisheries & Tenure Security. In press.
[91] R. Ruiz-Díaz, X. Liu, A. Aguión, G. Macho, M. deCastro, M. Gómez-Gesteira, E. Ojea, Social-ecological vulnerability to climate change in small-scale fisheries managed under spatial property rights systems, Mar. Policy 121 (2020) 104192.
[92] R. Ruiz-Díaz, X. Liu, A. Aguión, G. Macho, M. deCastro, M. Gómez-Gesteira, E. Ojea, Ojea, E., 2020. Social-ecological vulnerability to climate change in small-scale fisheries managed under spatial property rights systems, Mar. Policy 121 (2020) 104192.
[93] F. Santoro, S. Santin, G. Scowcroft, G. Fauville, P. Tuddenham, Ocean literacy for all: A toolkit, in: IOC Manuals and Guides, 80, IOC/UNESCO & UNESCO Venice Office, Paris, 2017.
[94] A. Schluter, C. Vance, S. Ferse, Coral reefs and the slow emergence of institutional structures for a glocal land- and sea-based collective dilemma, Mar. Policy 112 (2020) 2020.
[95] L. Schultz, C. Folke, H. Österblom, P. Olsson, Adaptive governance and natural capital, PNAS 112 (24) (2015) 7369–7374, https://doi.org/10.1073/pnas.1406493112.
[96] H.Z. Schuttenberg, H.K. Guth, Seeking our shared wisdom: a framework for understanding knowledge coproduction and coproductive capacities, Ecol. Soc. 20 (1) (2015) 15.
[97] K.C. Seto, S.J. Davis, R. Mitchell, E.C. Stokes, G. Unruh, D. Ürge-Vorsatz, Carbon lock-in: types, causes, and policy implications, Annu. Rev. Environ. Resour. 41 (1) (2016) 425–452.
[98] N. Shumway, R. Foster, B. Head, P. Fidelman, Policy solutions needed for the future of coral reefs, BioScience (2023) biad092.
[99] K.J. Siegel, R.B. Cabral, J. McHenry, E. Ojea, B. Owashi, S.E. Lester, Sovereign states in the Caribbean have lower social-ecological vulnerability to coral bleaching than overseas territories, Proc. R. Soc. BBiol. Sci. 286 (2019) 1897.
[100] P.V. Stefanoudis, W.Y. Licuanan, T.H. Morrison, S. Talma, J. Veitayaki, L. C. Woodall, Turning the tide of parachute science, Curr. Biol. 31 (4) (2021) R184–R185.
[101] R. Streit, T.H. Morrison, D. Bellwood, Coral reefs deserve evidence-based management not heroic interference, Nat. Clim. Change (2024) (in press).).
[102] F. Sultana, The unbearable heaviness of climate coloniality, Political Geogr. 99 (2022) 102638.
[103] S.G. Sutton, R.C. Tobin, Constraints on community engagement with Great Barrier Reef climate change reduction and mitigation, Glob. Environ. Change 21 (3) (2011) 894–905.
[104] Louise S.L. Teh, Lydia C.L. Teh, U.Rashid Sumaila, A global estimate of the number of coral reef fishers, PLoS One 8 (6) (2013) e65397.
[105] M. Tengö, E.S. Brondizio, T. Elmqvist, P. Malmer, M. Spierenburg, Connecting diverse knowledge systems for enhanced ecosystem governance: the multiple evidence base approach, Ambio 43 (5) (2014) 579–591.
[106] H. Terorotua, V.K.E. Duvat, A. Maspataud, J. Ouriqua, Assessing perception of climate change by representatives of public authorities and designing coastal climate services: lessons learnt from French polynesia, Front. Mar. Sci. 7 (2020) 2020.
[107] E.L. Tompkins, W.N. Adger, Does adaptive management of natural resources enhance resilience to climate change? Ecol. Soc. 9 (2) (2004) 10 ([online] URL:).
[108] R.A. Turner, J. Addison, A. Arias, B.J. Bergseth, N.A. Marshall, T.H. Morrison, R. C. Tobin, Trust, confidence, and equity affect the legitimacy of natural resource governance, Ecol. Soc. 21 (3) (2016).
[109] United Nations Environment Programme, Adaptation Gap Report 2020, UNEP, 2021.
[110] J. Vandenberg, A. Humphries, C. Garcia-Quijanoa, A. Moore, R. Pollnac, S. Abdullah, Assessing indicators and limitations of food security objectives in coral reef restoration, Conserv. Soc. 19 (1) (2021) 68–79.
[111] I. Wanzenböck, J.H. Wesseling, K. Frenken, M.P. Hekkert, K.M. Weber, A framework for mission-oriented innovation policy: alternative pathways through the problem–solution space, Sci. Public Policy 47 (4) (2020) 474–489.
[112] A. Wiechman, S. Alonso Vicario, E.A. Koebele, The role of intermediate collaborative forums in polycentric environmental governance, J. Public Adm. Res. Theory (2023) muad017.
[113] P.J. Woods, J.I. Macdonald, H. Bárðarson, S. Bonanomi, W.J. Boonstra, G. Cornell, G. Cripps, R. Danielsen, L. Färber, A.S.A. Ferreira, K. Ferguson, A review of adaptation options in fisheries management to support resilience and transition under socio-ecological change, ICES J. Mar. Sci. (2021).
[114] Christopher J. Wynveen, Stephen G. Sutton, Engaging the public in climate change-related pro-environmental behaviors to protect coral reefs: the role of public trust in the management agency, Mar. Policy 53 (2015) 131–140.
[115] S.S. Yadav, K.M. Gjerde, The ocean, climate change and resilience: making ocean areas beyond national jurisdiction more resilient to climate change and other anthropogenic activities, Mar. Policy 122 (2020) 104184.