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Marine governance to avoid tipping points: Can we adapt the adaptability envelope?

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ABSTRACT

Combined pressures from climate change, resources demand and environmental degradation could lead to the collapse of marine systems and increase the vulnerability of populations dependent on them. In this paper an adaptability envelope framework is applied to investigate how governance arrangements may be addressing changing conditions of marine social-ecological systems, particularly where thresholds might have been crossed. The analysis focuses on three Australian case studies that have been significantly impacted by variations or changes in weather and climate over the past decade. Findings indicate that, in some cases, global scale drivers are triggering tipping points, which challenge the potential success of existing governance arrangements at the local scale. Governance interventions to address tipping points have been predominantly reactive, despite existing scientific evidence indicating that thresholds are approaching and/or being crossed. It is argued that marine governance arrangements need to be framed so that they also anticipate increasing marine social-ecological system vulnerability, and therefore build appropriate adaptive capacity to buffer against potential tipping points.

1. Introduction

Some marine systems may have already reached undesirable states or tipping points that impede their recovery. While tipping points associated with climate change are difficult to predict [1], as marine systems approach undesirable ecological states, significant social and economic implications will follow [2,3]. This may in turn lead to social-ecological tipping points given the interdependence between marine ecosystems and human communities [4].

As marine systems become more exposed to climate related impacts, improved governance interventions are needed to address the vulnerability of marine social-ecological systems and enhance their adaptive capacity to help offset the potential impacts [5]. In this paper, a framework based on the concept of an adaptability envelope is used to distil lessons from interventions implemented in three Australian marine systems affected by extreme events. Such extremes will become more significant under climate change, not only climatically, but also in their effect on marine social-ecological system vulnerability. To this end, the paper is structured in four parts. The first clarifies the concept of the 'tipping point' and its implications for marine governance. The second describes the adaptability envelope analytical framework with case studies. The third presents findings from the case study analyses. Finally, the paper concludes by discussing improved outcomes of equipping governance arrangements with capacities to respond to both ecological and social-economic tipping points, particularly those related to climate change impacts.

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2. Conceptual underpinnings: tipping points and adaptive governance

Irreversible shifts or tipping points have conceptual origins in the palaeoecological literature [6,7]. The application to systems theory recognises equilibria and irreversible change – where irreversible change occurs when thresholds may be crossed, between stability and instability, and can be caused either by external forces or internal loss of strength [8].

More recently, the terms, 'tipping point' and 'threshold' are used interchangeably within the literature concerning both biophysical and human systems, and are subject to varied interpretations [9]. This paper follows definitions from the fields of ecology and environmental governance.

In ecology, a tipping point is an ecological threshold beyond which the system may experience a major change in ecosystem properties such as habitat structure, species composition or community dynamics [10]. Ecological thresholds are understood as the points at which changes in external conditions can lead to significant change in the structure or function of the ecosystem [11]. Crossing ecological thresholds inevitably has implications for social systems, as ecological and social systems are interlinked [11,12].

In environmental governance, tipping points indicate the moment of crisis giving opportunities presented to governance systems to take action [13]. In this context, thresholds comprise the point at which decision-makers start to act in the policy context, such as the introduction of new legislation or allocation of financial resources to support specific policies. In social contexts, tipping points can be defined as a technical or social point in which an indicator shifts 'from an acceptable to an unacceptable condition' [14]. Although social tipping points are commonly discussed, specific evidence is limited [15], in part because their existence depends on subjective judgements about the style and scale of change [16].

Cases of social-economic collapse following ecological collapse are perhaps best documented in fisheries and forestry dependent communities [17]. However, social tipping points may also lead to ecological tipping points. For example, some Māori groups in New Zealand assert that the inability to utilise their fisheries management methods is linked to local fish stock declines [18,19]. Anticipatory adaptation (e.g., in relation to climate change) can also result in social tipping points being crossed. In particular, Crane [20] highlights how regional climate adaptation processes designed to build social-ecological resilience in lagoon fisheries resulted in dramatic social change for one group, but enabled another to thrive. Thus, while social tipping points may exist, their causation is often complex.

In summary, tipping points comprise irreversible shifts in a given system due to thresholds being crossed [1]. Once these thresholds are crossed, the system dynamics change and are irreversible even after attempts at returning variables to a pre-threshold state [1]. These radical shifts in system dynamics and structure are variously referred to as 'collapses' or 'regime shifts'. The standard criteria for their definition includes "sudden, high-amplitude, infrequent events, which are detectable in multiple aspects of the physical and biological components [of a system] and on large spatial scales" [21, p. 106].

2.1. Tipping points and adaptive governance

The literature identifies four key underlying causes that may contribute to unsuccessful marine governance responses when attempting to deal with tipping points. These include the setting of inappropriate quotas and rules [22]; the institutional inability to address intergenerational equity [23]; the focus on rights instead of responsibilities [22]; and the emphasis on short-term economic gain over scientific advice [24]. Conversely, successful marine governance responses often include flexibility to make context-specific rules [25]; decentralised, collaborative decision making that involves the local community [26]; effective trans-national governance and certification [27]; a move towards adaptive governance [28,29]; or shifting from open access to a zoned regime with specific rights and responsibilities [30].

Several important implications for adaptive governance can be identified in the literature on tipping points. First, a tipping point can induce a governance change and the transition to a more resilient social-ecological system [29,31] if a well-managed step by step process is followed [32–34]. Second, adaptive governance concerning tipping points requires the promotion of an integrated approach that involves multi-level spatial governance [35], has a multi-species/multi-ecosystem scope, considers market dynamics, and is led by community concerns [23]. Additionally, it also requires collaboration between government, business and the community [27], and supportive governance networks involving all stakeholders [36] leading to ethical collaboration [37,38].

Adaptive governance may be suitable to address marine system tipping points because its overall purpose is to steer societies as they develop the capacity to adapt and transform their interactions with natural systems and prevent them from tipping towards undesirable development trajectories. Adaptive governance is relevant in situations where transformative change is necessary because it focuses on the complex relationships between people and natural systems, interactions within multilevel institutional settings, key drivers of transformation, and a learning approach to managing change and uncertainty [17,29,39,40].

Dietz et al. [41] and Folke et al. [29] identified a range of conditions or requirements for adaptive governance. These can be encapsulated in adaptive governance principles of:

- *connectivity*, implying institutional ability to undertake timely and coordinated action across multiple scales and ensure timely information about feedbacks occurring within human-nature systems to avoid surprises;
- *adaptability*, suggesting the ability of governance structures to deal with change and reorganise if considered beneficial or necessary;
- *reflexivity*, implying governance arrangements encompassing abilities for awareness, deep reflection and recursive responsiveness to changing conditions that enables learning, new knowledge and feedback signals to be incorporated into adaptive management action; and
- *transformability*, involving the governance regime having potential to navigate a shift to a new system direction when the existing system becomes untenable.

Good adaptive governance combines these specific principles with traditional principles of good governance – legitimacy, accountability, transparency, fairness and inclusiveness [42].

3. Research approach and methodology

3.1. The adaptability envelope

Marine systems face multiple threats; vulnerability to climate change, combined with existing pressures, could lead to the collapse of marine systems, therefore requiring adaptive governance [43]. Vulnerability thresholds to climatic extremes are a consequence of the potential impacts from exposure and sensitivity, offset by any adaptive capacity in the system. The 'coping range' [44] of a system may be strengthened by adaptive capacity that can be influenced by ecosystems autonomously adapting and/or governance arrangements that enable further adaptation. In line with Nunn et al. [45] in the human metabolism literature, such vulnerability thresholds can be characterised as the range defined by an *adaptability envelope*.

In a *stationary climate* – i.e., one that is assumed not to change substantially over time – ideal governance arrangements would be holistic in their consideration of the marine social-ecological system. Implicit in this notion they recognise that:

1. Vulnerability thresholds may be crossed, and are inevitable, but that the frequency and/or duration of such extreme forcing events are within acceptable limits (i.e., this represents the bounds of the system coping range); and
2. The system will include autonomous and planned adaptation that increases the vulnerability threshold.

Another way to interpret the role played by governance arrangements in extending the vulnerability threshold of marine social-ecological systems is through the lens of stability landscapes

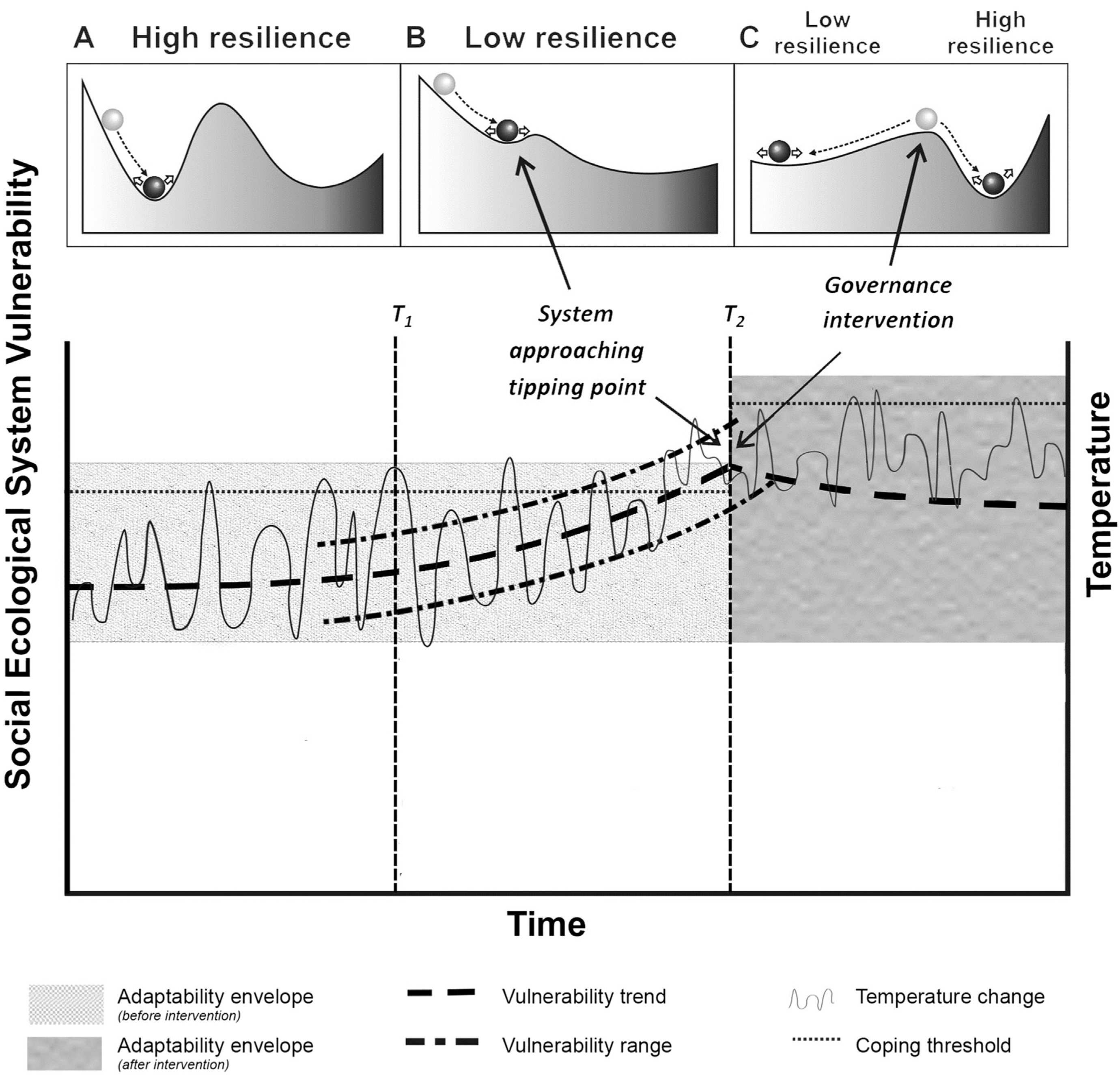

Fig. 1. Climate impacts, extremes, governance and the adaptability envelope (after [4,48,49,52,53]). *Notes:* In *Scenario A*, the frequency and intensity of extreme events are such that system vulnerability may occasionally get pushed beyond the coping threshold; however, the system remains within the adaptability envelope and is essentially resilient. In *Scenario B*, the system is subject to more frequent and intense extreme climate events (e.g., extreme hot or cold temperatures) pushing it outside the adaptability envelope more often, reducing system resilience and increasing the likelihood of the system tipping over into a less desirable, highly vulnerable, low resilience state at T_2. In *Scenario C*, governance interventions have diverted the system from the approaching threshold. Instead, by expanding the adaptability envelope through fostering increased adaptive capacity and reducing sensitivity and exposure to extreme climate events, the governance interventions helped to avoid a regime shift and nudged the system towards a new pathway or towards a deeper attraction basin and thus a less vulnerable, more resilient state. The vulnerability trend is lowered but is unlikely to revert to its Scenario A position.

as featured in resilience thinking, where resilience is proportional to the size and depth of the basin of attraction [46]. Appropriate governance interventions can contribute to system resilience through maintenance of a large, deep basin of attraction (that is, the system remains within the attraction basin and is stable). Such a governance regime might be one that focused on maintaining system resilience by, for example, accelerating the recovery rate after an extreme event (see Fig. 1 of [47]).

In a *changing climate* – in particular, one that is affected by a climatic trend, and thus changes to the probability distribution including the probability of climatic extreme events (e.g., see Fig. 3 of [48]) – the desirable governance arrangements would not only take into account the two numbered points above for the case of a stationary climate. They would additionally facilitate and factor into planning both medium-term (20–50 years) and long-term (50–100 years) climate projections of extreme events and their likely social-ecological system. To be effective, these governance arrangements should:

1. Take account of reliable information from climate projections, and
2. Set effective limits to vulnerability (i.e., a revised 'adaptability envelope').

An important corollary from resilience thinking's stability landscapes concept is that without appropriate governance arrangements, the distinct likelihood is that more frequent, intense or longer duration extreme events (resulting from climate change) will reduce the size of an attraction basin, destabilising it, and eventually tipping the focal system over a threshold into a shallow attraction basin where there is increased instability and reduced productivity and resilience (see Fig. 1 of [49]; see also [50]). In other words, the system shifts outside the adaptability envelope into a dangerous space. Fig. 1 explains the relationships between social-ecological vulnerability to climate change, including the adaptability envelope concept, and stability landscapes diagrammatically.

3.2. Australian case studies

Three critical Australian cases [51] were selected to illustrate how [potential] tipping points affecting marine systems are being addressed by governance responses: Moreton Bay in South East Queensland (SEQ), the East Coast of Tasmania rocky reef ecosystems, and the 2011 marine heat wave off the Western Australia coast (WA) (see Fig. 2). The cases offer suitable scope to generate insights that can inform governance arrangements to better manage the changing conditions affecting marine social-ecological systems, particularly to avoid cascading social-economic tipping points associated with inappropriate governance arrangements. The cases were selected on the basis that:

(1) they are exemplars of different state jurisdictions within the Australian context and, therefore different governance arrangements;

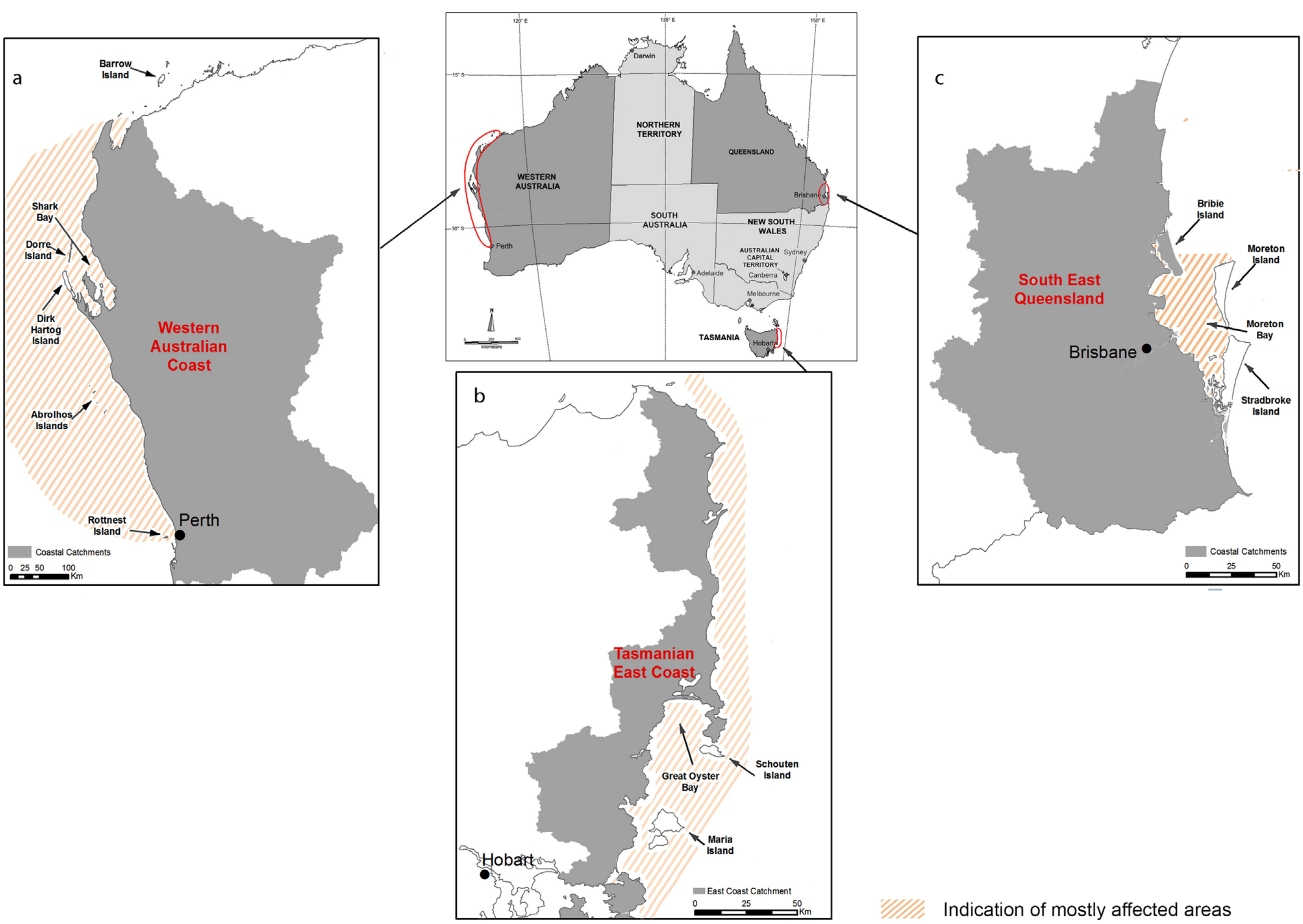

Fig. 2. Case study areas. Hachure marks indicate: (a) the extent of worst affected area by the 2011 marine heat wave off the Western Australia Coast at its peak in February 2011 [60,61]; (b) the range expansion of sea urchin and where barren patches of seaweed habitats have been observed off the East Coast of Tasmania [56,57]; (c) the marine area of Moreton Bay impacted by run off from in-land and urbanised catchments (dark grey area) carrying sediment loads and pollutants [71].

(2) their regime shifts due to changed environmental conditions have been well-documented;
(3) the social-economic impacts caused by the regime shift upon local industries and communities have also been documented; and
(4) they are informative in illuminating both the complex drivers of a productive ecosystem towards a tipping point and the influence that governance and management arrangements can have in reinforcing or varying this trajectory.

Utilising the adaptability envelope framework, the case studies are critically reviewed and analysed. In all cases insights are

Table 1
Analytical summary of the three Australian case studies.

Characteristics	Moreton Bay-SEQ	East Coast Tasmania	Western Australia Coast
Latitude/longitude	27°03S/152°50E 27°54S/153°27E	40°50S/148°13E 42°45S/148°10E	20°30S/112°30E 32°30S/115°30E
Area (km^2)	3400	8000	2.5 million
Population in adjacent region (approx.)	3 million	10,000	1.8 million
Overview	Vulnerable ecosystem (coastal floodplains and wetlands; coral and seagrass habitats) with cumulative impacts from land and weather that affect marine management.	Lobster fishery in decline despite reductions in Total Allowable Catch, most likely related to the spread of sea urchin barrens.	Unpredicted marine heat wave resulting in: dramatic fisheries, seagrass and seaweed declines; coral bleaching; and algal blooms.
Observed environmental change	The species of sub-tropical marginal coral reefs [53] have shifted from branched corals to massive *Flora* corals. This shift appears to have occurred from the mid-1800s to the mid-1950s, coinciding with substantial development in the region, suggesting that anthropogenic effects had impacted on the coral reefs [53]. Deteriorating water quality, particularly increased nutrient loads and suspended solids, has been linked to loss of coral in the Bay [54].	Changes to the Eastern Australian Current have led to sea urchin (*Centrostephanus rodgersii*) larvae being carried further south, and the warmer temperatures have encouraged its spread into the area [55,56]. As a result, productive kelp (*Macrocystis pyrifera*) beds have become urchin dominated 'barrens' [57,58]. Their spread has impacted upon the rock lobster population (*Jasus edwardsii*) [59], in turn, encouraging further expansion of the barrens and a severe decline in the rock lobster population [59]. The rock lobster is the primary predator on the urchin, but only above a certain size, and it is these larger lobsters that are legally allowed to be commercially caught [58].	A large marine area off the WA coast was affected by a marine heat wave in the 2010/11 summer. The 'Ningaloo Niño' heat wave comprised an increase in a sea surface temperature anomaly of about 3 °C, thus outside the ± 1.5 °C monthly variation range and influenced summer rainfall [60,61]. The heat wave led to the first coral bleaching event in the Ningaloo Reef and substantial mortality of fish, lobster and abalone of high economic value [61].
Optimum ecological state	Branched corals and seagrass.	Productive kelp with rock lobsters, high species diversity (approx. 300 species).	Coral reefs and associated fisheries.
Sub-optimal ecological state	Massive *Flora* corals and seagrass loss [53].	Urchin dominated barrens, low species diversity (approx. 70 species), reduced productivity [57,58,62].	Bleached coral [63,64], algal blooms [65,66] and fisheries loss [61].
Ecological threshold crossed (irreversible shifts)	Threats to corals and dugongs, reduced recovery of seagrass in some areas of the Bay but no collapse [10].	Partial collapse, loss of kelp, urchin barrens could eventually cover approx. 50% of rocky reefs [57,59]; hysteresis and/or recovery much slower than degradation [67,68].	Mortality in seagrass, coral and some fisheries [69], changes in species distributions [61,70].
Trigger point for governance intervention (moment of crisis or opportunities)	Increased nutrients and turbidity from land run-off, poor water quality [71,72].	Decline in rock lobster abundance [59].	Marine heat wave, increased temperatures.
External forces (or intrinsic owing to reduced internal strength)	Flood and catchment land-use change (industrial, urban & agricultural) resulting in both acute and prolonged increases in water nutrient and suspended solids loading [54,73], fisheries management [74].	Hotspot region of warming waters due to multi-decadal southward extension of East Australian Current [55,75], over harvesting of lobster [56,58,68,76], transferable quotas reducing owner responsibility [77–79].	Surge in Leeuwin current, strongest every recorded La Niña [80], a long-term warming trend [69,81] and a cyclone.
Implications for interlinked social system	Tourism, fishing and amenity decline [82].	Fisheries demise and tourism decline, loss of livelihoods [77,83].	Effects on fisheries, tourism, livelihoods, with Abrolhos Islands community collapsing [84].
Social threshold (from acceptable to unacceptable; social-economic)	Commercial fishing demise, impacts on recreational boating and diving.	Rock lobster fishery demise, poor implications for social-ecological system.	Abrolhos commercial fishing community demise.
Management Responses	Healthy Waterways Partnership established to promote collaborative, adaptive management approach to regional water quality management on a voluntary (non-statutory) basis. The Partnership collated substantial scientific data to support government investments in stormwater quality improvement, waterway management and restoration.	A Quota Management System (QMS) was implemented through consultation between fisheries stakeholders and government, but with limited involvement and collaboration of conservation groups.	Fishery management responses (e.g. individual transferable quotas) and trial recovery efforts were put in place. There was also significant institutional collaboration to share and analyse data.
Outcomes from management responses	Some control of point-source pollution led to slowing decline in water quality into Moreton Bay, but there was limited success in implementing land use changes to improve water quality.	Self-regulated markets and QMS resulted in strong investor control of the rock lobster fishery and limited government management for public good outcomes. The focus was on resource management over conservation with limited collaboration and learning.	Timely and prudent management intervention in the lobster fishery supported moves towards ecosystem management, but had unintended impacts on the economic and social life of fishers, due to limited consultation with the fishing industry.

extracted to inform governance arrangements to better manage the changing conditions affecting marine social-ecological systems. This is done by applying the four adaptive governance principles outlined in Section 2.1 to distil implications for adaptive marine governance in light of climate change.

Data collection comprised an intensive desktop analysis of publicly available technical reports, journal articles, and statutory and non-statutory government documents for each case study. A summary of each case study is provided in Table 1.

3.3. Appraising adaptive governance in the three case studies

3.3.1. Connectivity

Improving connectivity through well-orchestrated cooperative and collaborative efforts is a critical component of adaptive governance to deliver timely and coordinated actions to better manage environmental change and avoid thresholds being crossed [29]. The three case studies showed initiatives toward establishing multi-stakeholder/agency collaboration seeking to deliver more integrated governance responses to address their specific environmental changes. However, so far, these initiatives have failed to implement effective coordinated action across multiple scales.

The *SEQ Regional Water Quality Management Strategy* was developed in the mid 1990s to address water quality issues in Moreton Bay at the regional scale [85,86]. The Strategy focused on setting water quality objectives aimed at reducing the impact of point and non-point sources of wastewater [86]. Since then, there has been significant effort to engage multiple stakeholders across the region to achieve improved water quality objectives for Moreton Bay [85]. Specifically, initiatives such as the *SEQ Regional Water Quality Management Strategy*, and the more recent *SEQ Healthy Waterways Partnership*, sought extensive stakeholder engagement and consultation, and formulated a shared vision for the Bay focused on pursuing healthy ecosystems to ultimately support people's livelihoods and lifestyles [85]. In particular, the *Healthy Waterways Partnership* endeavoured to adopt and support an adaptive management approach based on best available science to guide management decisions. However, although it delivered better control of point-source pollution, the extent to which it resulted in other on-ground land use changes that effectively contributed to improving the Bay's water quality is limited [87].

In Tasmania, the *Living Marine Resources Management Act 1995* promotes the sharing of responsibility for resource management and planning between government, industry and community through processes of stakeholder engagement and collaborative management. The Act contains provisions that promote capacity, coordination and adaptive management [59]. Fisheries stakeholders and government consult over management plans and development of fishery rules, such as the annual total allowable catch and resource sharing arrangements between commercial and recreational fishers. However, in practice this has overwhelmed conservation concerns so that connections between fisheries management and conservation agencies are virtually non-existent and management occurs in silos. Additionally, constrained by limited resources, state agencies have little interaction with local government or local communities to undertake broader engagement and facilitate multi-stakeholder collaboration [88].

In the case of Western Australia, the marine heat wave triggered institutional collaboration to make sense of diverse monitoring data gathered by multiple agencies including web-based community databases [69,89]. Specific fishery management responses were put in place, such as individual transferable quotas, and collaboration in monitoring and data sharing has been ongoing, supporting ecosystem based fisheries management. However, while management intervention in the lobster fishery was considered prudent and timely, there were unintended impacts on the economic and social life of fishers and their families as a result of low (to no) priority given by fishery managers to consult with the fishing industry [90].

3.3.2. Adaptability

Following the connectivity principle, adaptability comprises the capacity of stakeholders/actors to manage current and future change that is difficult to predict and carries known uncertainty supported by monitoring, evaluation and reporting systems [29]. There was evidence of the limited capacity governance responses have to effectively manage complex observed environmental changes in the three cases. In particular, the nature of the environmental change observed in the Tasmanian and Western Australian cases highlighted exogenous ecological limits to adaptation exemplified by crossed thresholds (see Table 1) and inherent limits to governance responses [91]. Notably, the principle of adaptability in the cases is perhaps best exemplified by, and restricted to, efforts seeking to improve multi-stakeholder and multi-agency collaboration to respond to observed changes.

In Moreton Bay, despite the efforts to improve agency collaboration, so that responsibilities to improve water quality were distributed among different actors, institutional arrangements encouraged them to operate independently within the broader programme. This led to competition for resources, limiting efforts to foster practical action [92]. Additionally, no specific programme was created to support the control of non-point sources of pollution through greater compulsory investment of landholders' private resources (time and money). Consequently, on-ground interventions were predominantly voluntary and fell short of addressing regional changes in land cover and land-use intensification long associated with reduced ecosystem health in waterways [87]. For example, Leigh et al. [87] estimated that more than half of the SEQ region's channel network (about 48,000 km) is considered to be in poor ecological condition and reversing this situation would be an overwhelming task due to its spatial scale and need for significant public and private economic investment.

In Tasmania, a Quota Management System (QMS) was adopted by the industry in 1998 to manage declining stocks of rock lobster [77]. Despite this, Bradshaw [77] (querying whether the QMS contributes to compliance, co-management and sustainable practices) highlighted rigidities resulting from privatisation of the resource through individual transferable quotas and the subsequent relinquishment of responsibility for sustainable outcomes by the state to the market [93]. While setting a Total Allowable Catch should be sufficient to manage declining stocks of specific species, its implementation was problematic by being focused on the economic profitability sought by industry investors. Consequently, a resource management culture and governance regime that privileges quota holders' vested interests may inevitably limit system capacity to implement adaptive governance and management arrangements able to deal with current and future environmental change.

Fishery managers and scientists in Western Australia have identified the importance of management arrangements that are flexible enough to rapidly respond to climate variability [89]. Some trial recovery efforts and review of existing management measures (e.g., fixed zones) will provide insight to possible responses [69,70,89]. Adaptive responses require ongoing monitoring, early detection of trends, improved modelling and predictive capacity of future environmental change, therefore contributing to expanding the system's adaptability envelope by identifying the future patterns of these trends.

3.3.3. Reflexivity

Robust governance seeking to manage environmental adaptation and change need not only be supported by trustworthy information but is also capable of incorporating new information and institutional learning as these become available [29,41]. Despite availability of significant scientific information and data regarding changed environmental conditions in all case studies (see Table 1), there is limited evidence that such information is being applied to guide governance responses.

The *SEQ Healthy Waterways Partnership* enabled the collation of substantial scientific evidence of the state of Moreton Bay regarding water quality and supported government investments in projects targeting stormwater quality improvement, waterway management and restoration projects. Despite this evidence, land-use practices across the broader regional scale – a key driver for declining water quality – remained predominantly unchanged [85,87].

Governance responses targeting the complex problems affecting the Tasmanian East Coast show preference for biophysical and economic over broader social considerations [88]. Furthermore, within the biophysical domain, scientific advice is weighted towards resource management over biodiversity protection [88]. Additionally, responsibilities often attributed to government authorities have been transferred to self-regulated markets, such as the introduction of an individual transferable quota system that resulted in strong investor control of the rock lobster fishery and limited government management for public good outcomes [77,93]. Hence, social-ecological or resilience learning is limited by the immaturity of current governance and management arrangements (e.g., integration of diverse perspectives and knowledge systems is crucial to understanding the dynamics of social-ecological systems under conditions of variability/change in order to explore alternative options).

While WA fisheries managers and scientists appear to be collaborating in managing biophysical information for institutional learning, it is only recently that there has been an effort to foster information exchange about climate impacts with the lobster fishing industry and general community [90].

3.3.4. Transformability

The transition to a new system trajectory, in light of impending tipping points, comprises a key feature of transformability. Indicators in each of the three cases show that there is indeed an approaching regime shift – and in the Tasmanian case this shift may have already occurred (see Table 1). Nevertheless, governance arrangements for the three cases appear to have limited ability to both support and implement such transition. Significant deficiencies in crucial aspects of the broader marine governance arrangements may also undermine the capacity to manage for, or avoid, tipping points.

The marine governance case provided by Moreton Bay clearly indicates that management strategies need to be implemented at a regional scale to be effective. While multiple scales from local to regional were considered and collaborative decision making and stakeholder engagement led to some successes, in spite of evidence of problems, lack of programme adaptation at the regional level due to inflexible programme structure limited effectiveness of non-point pollution reduction efforts [92]. Even though the collaborative regional waterway health management initiatives have triggered innovations in the regional resource governance systems, they fell short of reflexive learning leading to transformability of the governance system. Transformability is further compounded by the large spatial scale that governance responses need to account for [87], pressure to accommodate ongoing population growth through expanding urban development at the expense of environmental conservation of critical areas such as riparian zones and mangroves, and lack of continual funding to support both rehabilitation and monitoring programmes.

Prospects for governance transformation in the East Coast Tasmania case appear limited as adaptive governance performance has been assessed as poor [88,94]. Aspects of good adaptive governance, critical to coping with tipping points, including possession of systems understanding, innovation capacity, management for uncertainty and complexity, governance integration, collaboration and engagement, leadership, and buffering capacity, were found to be inadequate. Adaptive management is in its infancy and administration is scattered and siloed across agencies. Historical divisions between dominant resource and weaker conservation agencies are compounded by weak coordination between governance levels, while engagement and collaboration initiatives are overtaken by polarised political views, and non-existent formal advisory and consultative processes. Agency managers tend to be conservative and inflexible, hence neither open to change or new ideas, nor able to take advantage of opportunities provided by change, key preconditions for responding to system change [88].

A regime shift seems possible in the Western Australian coastal domain. Since the 2011 marine heat wave, Western Australian sea surface temperatures have remained high at 1–2 °C above average, and are expected to rise permanently by 1–2 °C in the next 50 years. Range extension has been recorded for several near-shore finfish species and a continuing southward range shift in marine biota is expected in the future. Some species have had slow recoveries (e.g., scallops, blue swimmer crabs and abalone) and coral and seagrass will be increasingly vulnerable in the future [81,89]. There is recognition of the need for reduction of additional anthropogenic effects which add stress to effects of a changing climate that cannot be so easily managed [69,89]. Transformative governance initiatives beyond improved stakeholders' collaborative efforts are needed to address observed (see Table 1) and future environmental changes in the Western Australian coastal region.

4. Implications for adaptive marine governance under a changing climate

Drawing on the concept of the adaptability envelope, it can be argued that governance arrangements play a critical role in increasing the vulnerability threshold of a marine social-ecological system to future regime shifts and promoting system resilience [46,47]. Conversely, when an appropriate adaptive governance regime is absent, systems may exhibit reduced resilience and increased instability, and thus a greater likelihood of crossing critical thresholds that will shift the system outside the adaptability envelope [49,50] (see Fig. 1). The cases investigated by this paper offer important lessons that can inform governance arrangements seeking to manage climate-induced environmental change that may lead to both ecological and social-economic tipping points. Key lessons include interconnected matters of scale in drivers and governance responses, timing of governance interventions, and support for governance interventions to address uncertainty.

4.1. Scale in drivers and governance responses

The approach towards tipping points can be induced by multiple stressors that weaken the system, pushing systems closer towards a regime shift. These stressors are generated at different scales and therefore demand responses that are scale- and context-specific and acknowledge their limits in promoting adaptation and transformation where necessary. Specifically, drivers causing observed environmental changes in the Tasmanian East Coast and Western Australian Coast are typically much larger in scale (e.g., warming currents and ocean surface water temperatures [55,69,75,80,81]), whereas drivers in Moreton Bay to date are primarily regional [54,73]. Environmental changes induced by global drivers are beyond the control of locally based governance arrangements. Governance responses ought to focus on their resource dependent communities to adjust to future social-economic tipping points that are likely to follow from crossing ecological thresholds (e.g., increase in urchin barrens along the Tasmanian East Coast [59], changes in species distributions along the Western Australian Coast [61,70]).

Environmental change that is predominantly affected by regional drivers, such as in Moreton Bay, is well served by governance responses that target changes in regional land use and urbanisation and focus on prevention and mitigation to avoid crossing thresholds. Without strategies that recognise catchment-coast connectivity, marine environments located adjacent to highly urbanised regions will continue to be threatened by land use practices, and uncoordinated governance responses are likely to have little impact. There is the possibility that the marine ecosystem in those areas could undergo total collapse if climate change impacts and impacts from development are both high [72]. Additional extreme events (anticipated under climate change, such as cyclones and marine temperature increases) will further exacerbate the challenge of environmental change, and increase the impetus for a regional and integrated governance approach to water quality in the region. Moreover, attempts to prevent one type of tipping point (e.g., fisheries collapse) may cause stress in another area such as social-economic (e.g., impact on fishers' livelihoods) [74]. Without addressing the cause of the main stressor to the system, such management responses are ‘tinkering around the edges’ and not changing its adaptive capacity.

Both globally and regionally driven environmental change require a shift from an emphasis on specific resources (e.g., fish) to adaptation of the social-ecological system as a whole. This shift could adjust the adaptability envelope by stimulating establishment of a more integrated and adaptive marine governance regime that is better equipped to manage and negotiate potential tipping points.

4.2. Timing of governance interventions

The case studies concern systems that are on the edge of the range of their adaptability envelope with recognisable changes in their ecosystem structures (see Table 1). Nevertheless, governance interventions were predominantly reactive and occurred either after thresholds were crossed or when their threat was imminent. Scholars [49,50] suggest that an indication that a system may be approaching a tipping point is its slow recovery from perturbations. For example, in northern Moreton Bay, seagrass habitats have not recovered from a major flood event that occurred 20 years ago despite recent improvements in water quality due to controlled point sources of pollution [95]. This slow recovery from perturbation may be related to chronic stress from downstream impacts. In contrast, the capacity of coral habitats to withstand the impacts of the 2011 floods could be attributed to the fact that these coral habitats have been acclimatised by a range of environmental pressures close to critical thresholds for coral survival [96]. As noted by Scheffer et al. [50], repeated recovery from small-scale perturbations could mask approaching tipping points by giving a false indication that the system is resilient. Thus, avoiding tipping points requires the establishment of governance that can be adaptive should the need arise, and concomitantly enables the adaptability envelope to change reflexively.

Deciding the time for governance intervention is not a straight forward process; however interventions are critical if ecological and social-economic tipping points are to be avoided, and for the system to maintain its resilience by staying within an adaptability envelope (see Fig. 1). While there are challenges in improving the anticipation of critical transitions that will shift the system [50], governance interventions concerning marine systems need to consider planning for future extremes and raised temperatures to avoid major ecological, social and economic consequences. In particular, the implementation of anticipatory long-term policies to protect climate-sensitive systems from collapse, including protection of marine systems and associated natural resources that sustain local communities, will contribute to reducing economic costs of future unavoidable adaptation needs [97]. These pre-emptive policies could also contribute to reducing vulnerability and building buffering capacity of existing systems that are already at risk. For example, the implementation of marine parks is a form of pre-emptive (or no-regrets) policy and constitutes both a precautionary (governance) and conservation (management) measure that can assist social-ecological systems to shift away from tipping points, providing that policy trade-offs are also considered to avoid cascading negative effects on resource dependent communities.

As environmental changes can occur slowly over long time periods and are difficult to detect, governance interventions need to be supported by improved monitoring programmes focused on key indicators that are scale- and context-specific. These monitoring programmes enable the compilation of long-term time series data that are critical to improve our understanding of ecosystems. Hence, they facilitate the anticipation of tipping points and provide guidance to the type and time of interventions seeking to adapt the system adaptability envelope.

4.3. Supporting governance interventions under uncertainty

There are significant uncertainties in anticipating both ecological and/or social-economic regime shifts [50], with repercussions for proactive governance intervention. A large body of research confirms that action on climate change is significantly impeded by uncertainty concerning climate science [98–100]. Research in the Australian context shows that proactive governance intervention targeting climate change impacts is equally hampered by lack of political support [101–103]. The Moreton Bay case confirms the absence of strong political will to implement region-wide measures despite substantial scientific evidence of the state of the Bay's water quality [85]. On the other hand, the importance of scientific evidence is highlighted by the Western Australian case. Because of the long time series of data about the Western Rock Lobster fishery, pro-active management reduced the fishing effort from 2008/9 when low settlement and recruitment were first detected and assumed to be due to long-term environmental trends. This action ensured that spawning stock remained at sustainable levels during the period of the heat wave.

Significant deficiencies exist in crucial aspects of coordination of marine governance arrangements, which may also undermine the capacity to manage for, or avoid, tipping points. These deficiencies are best documented in the Tasmanian case where system integration and coordination required for coping with tipping points is similarly lacking within the governance system, with a few dominant individuals adopting limited formal processes. Despite a governance and management regime that was until recently able to maintain the lobster resource and fostered cooperation among managers and fishers, the combination of primary and secondary climate change impacts interacting with management controls favouring the taking of larger lobsters and failure to curtail recreational fishers' take has resulted in declines in fish abundance [104]. Thus, absence of adequate coordination processes to secure cooperation from all stakeholders and buffering capacity deficiencies – such as, fragmented and under-resourced interest groups and a lack of marine conservation personnel and resources – are helping to steer the social-ecological system beyond its current adaptability envelope. In Moreton Bay, a lack of coordination and integration of interests subsequently meant that interventions failed to consider policy trade-offs, as seen through the rezoning of the Marine Park that increased impacts of the no-take zones on commercial fishers (e.g., loss of fishing grounds, overcrowding, higher operational costs, and need for diversification) [74].

Patterson et al. [92] argue for the critical importance of building diverse enabling capacities (including prior experience and contingency; institutional arrangements; collaboration; engagement; vision and strategy; knowledge building and brokerage; resourcing; entrepreneurship and leadership; reflection and adaptation) at both the local catchment level as well as at broader regional policy and governance levels in order to implement practical action. Support for governance interventions under uncertainty thus requires several improvements to current practice. First, a well-managed process will require improved cross-agency, -scale and -jurisdictional integration and collaboration. For example, in situations similar to the Tasmanian case, where increased frequency of algal blooms in recent years has necessitated closure of some fisheries, including rock lobster, continuing occurrence of blooms and substantive impacts on resource users' livelihoods as a consequence could well provide a window of opportunity to adjust the adaptability envelope by building adaptive components into the marine governance system. Thus, monitoring of fisheries and aquaculture operations to mitigate impacts of algal blooms and other water quality problems could strengthen coordination between sector-oriented agencies and increase support for institutionalising integrative processes. Coordination could be facilitated through the development of appropriate policy frameworks for the marine social-ecological system, establishing formal commitments, setting high level governance principles, and formalising key elements of governance. This approach would extend and facilitate linkages between government levels as well as engagement with a more diverse range of interests such as natural resource management bodies, local governments, community and other stakeholders.

Second, as seen in the Western Australian case where long term trends, decadal shifts and extreme events of climate change are having a major impact on fish stocks and fisheries livelihoods, management arrangements need to be flexible enough to rapidly respond to climate variability. Last, the frequency and intensity of extreme climatic events have major implications for predictive models of species distribution and ecosystem structure, which are largely based on gradual warming trends [70]. However, based on the Western Australian and Tasmanian cases, even relatively small temperature increases in ocean waters can have devastating effects on existing ecosystems. In the face of uncertainty, governance interventions could be more effective if worst case scenarios were considered to capture the extent of risk that environmental changes are likely to pose to social-ecological systems.

The cases indicate that governance interventions seeking to avoid tipping points and adjust the adaptability envelope of social-ecological systems (see Fig. 1) require early detection of trends to ensure adequate governance and management strategies can respond in a timely way. Key to timely responses is the implementation of ongoing reflexive decision-making [105] based on monitoring programmes that support the collation of long term data. These monitoring programmes would enable early detection of critical environmental change and assess the efficacy of implemented measures, including policy trade-offs leading to cascading tipping points. To enable robust monitoring to occur, the appropriate identification of indicators is critical. In particular, indicators need to be scale- and context-specific whilst focusing on the whole social-ecological system rather than specific resources.

Perhaps marine governance systems could also learn from the disaster management experience and plan interventions to avoid tipping points following a dynamic interpretation of the prevention, preparedness, response and recovery paradigm [106], especially recognising windows of opportunity for transformation and action [105]. In doing so, governance systems can be supported by evidence (e.g., monitoring data) to adopt acceptable levels of risk and select trigger points to guide interventions as tipping points threaten social-ecological systems (see Fig. 1). In particular, an adaptive marine governance system focused on adapting the adaptability envelope of social-ecological systems is one that is prepared for the approaching tipping points by anticipating action to avoid them. It is also a governance system that can respond to, and deal with, the consequences of unavoidable tipping points through planned recovery carried out during identified windows of opportunity.

In summary, a transformative and adaptive marine governance system that can extend the adaptability envelope of social-ecological systems at risk of tipping points related to climate impacts requires: decisions that are informed by science; political leadership and willingness to respond proactively, be precautionary, take risks, innovate and experiment when responding to unforeseen tipping points; and a governance regime supported by reflexivity that fosters transformability.

5. Conclusion

Three Australian case studies illustrate the vulnerability of marine systems that may be approaching social-ecological tipping points. Moreton Bay represents a system under chronic stress caused by region-wide land use practices, which could collapse if an additional climate change stressor (e.g., increase in sea water temperature, ocean acidification) is added to the equation. The Tasmanian example reveals a resource management system that has been responding to resource decline for many decades but, additionally, must now deal with the highly complex impacts of ocean warming that have taken the social-ecological system to the outer limits of its adaptability envelope. Without governance innovation to foster coordination between agencies, resource users, scientists, non-government organisations, and affected communities, the outlook for these productive temperate rocky reef ecosystems is uncertain. The large spatial scale of the WA marine heat wave event, accompanied by the persistent 1–2 °C sea water temperature warming experienced along the WA coast over the past eight years, is already transforming the environment, with fishing industry and communities significantly impacted. In the Abrolhos Islands (see Fig. 2), this represents both an economic and broader social regime shift.

The adaptability envelope (see Fig. 1) was utilised to conceptualise how adaptive governance interventions can reduce the vulnerability of climate-impacted marine social-ecological systems to tipping over into low resilience states. In particular, adaptive governance can help to increase the adaptability envelope by raising the threshold at which tipping points are crossed. By applying the adaptability envelope to the three critical case studies, the specific governance needs required to avoid tipping points in marine social-ecological systems were identified. This may be facilitated by better anticipation of tipping points through targeted system monitoring and holding a clearer understanding of what the worst case scenario may be. While deliberate action is needed to improve marine governance through better collaboration and integration of agencies and different forms of knowledge and interests into decision-making [107], this study highlights that knowledge sharing must occur at, and between, multiple scales. Local action will however make no difference if global drivers of climate change push systems beyond their adaptability envelope, requiring investment in more innovative adaptation. To understand the complex dynamics of social-ecological systems operating at the limits of the adaptability envelope and to be able to innovate requires reflexive governance characterized by openness to new information and inclusion of diverse perspectives and knowledge sets in decisions. Ideally, systems operating at their adaptability limits would also have in place governance arrangements capable of proactively dealing with unexpected changes. In effect, the risks posed to marine social-ecological systems by climate change mean we must build our capacity for collective agreement about how to be reflexively adaptive and transformative if necessary.

There may be also benefits in using the adaptability envelope for understanding change in social-ecological systems, particularly in terms of its potential to communicate to stakeholders the ways in which change occurs. To fully support such benefits future context-specific research is required to identify the limits of the adaptability envelope, including, but not limited to, indicators and monitoring of local knowledge and how it is used. Additionally, future research is also needed to better understand which interventions (e.g., by how much, time lags etc.) are required by the system to increase its adaptability envelope and therefore avoid crossing tipping points.

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