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Are we ready for ocean acidification? A framework for assessing and advancing policy readiness

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Abstract

Effective climate policy that addresses carbon dioxide emissions is essential to minimizing and addressing the impacts of ocean acidification (OA). Here we present a framework to assess the readiness of OA policy, using coral reefs as a focal system. Six dimensions encompass comprehensive preparation by ecosystems and societies for the impacts of OA and other anthropogenic hazards: (1) climate protection measures, (2) OA literacy, (3) area-based management, (4) research and development, (5) adaptive capacity of dependent sectors, and (6) policy coherence. We define standardized indicators, identify leading countries, and evaluate the case study of Australia, the country with the largest coral reef system. The framework provides a rubric for a government unit to self- assess strengths and weaknesses in policy preparedness and to prioritize future endeavors.

Ocean systems are experiencing exceptional warming and ocean acidification (OA) as consequences of unchecked greenhouse gas emissions [1]. As carbon dioxide has increased in the atmosphere, a substantial proportion (~24% of total fossil fuel emissions since preindustrial times) has entered the upper layers of the ocean where it has combined with water to reduce the pH and change the concentration of key ions such as carbonate and bicarbonate [2]. This process is referred to as OA. Since the beginning of the Industrial Revolution, the pH of the surface ocean has decreased by 0.1 units, representing a 26% increase in acidity [1]. This rate of ocean chemistry change is unrivalled in the past 65 million years, if not the past 300 million years [3]. Our understanding of OA and its impacts is at an early stage. However, a growing number of laboratory, field, and modeling studies have revealed that a variety of fundamental biological processes are sensitive to OA, including primary productivity, calcification, decalcification, nutrient cycles, reproduction, development, and gas exchange [4]. Given these results, it is not surprising that a broad range of marine organisms are affected by OA including bacteria, algae, invertebrates, and fish [4].

Minimizing and addressing the impacts of OA is a specific target of the United Nations (UN) General Assembly's Agenda for Sustainable Development under Sustainable Development Goal (SDG) 14.3 [5].

OA was also recently adopted as a Global Climate Indicator [6] by the World Meteorological Organization in its reporting to the Conference of the Parties of the United Nations Framework Convention on Climate Change to inform governments, international agencies, and the general public about the global climate. The UN has also launched the Decade of Ocean Science for Sustainable Development (2021–2030, www.oceandecade.org) to facilitate cross sector collaboration on development of frameworks and tools that inform policies required for the sustainable development of the ocean, and to support the UN 2030 Agenda for Sustainable Development and associated SDGs. In support of these goals, we present a framework to help assess the readiness of policy pertaining to OA—using one of the most vulnerable marine ecosystems, coral reefs, as a focal system—with the goal of helping guide current and future policy to tackle OA.

1. Six key dimensions of policy preparedness

Understanding what steps to take and how to insert the best available science into policy action on OA is critical for successfully intervening on OA's impacts [7, 8]. The development of policy on OA has many co-benefits, including helping achieve national contributions to global CO_2 emissions targets, sustainable development goals, the post 2020 global biodiversity framework targets, supporting new industries and employment, and contributing to science and technology innovation [9]. Because OA policy development is at a relatively early stage, it can be developed to maximize co-benefits and harmonize with existing policy frameworks.

Here, we identify six dimensions that encompass a comprehensive suite of actions that must be taken into consideration as part of OA policy, so that ecosystems and societies are prepared for the impacts of OA along with other anthropogenic hazards (e.g. warming, sea level rise, oxygen loss, eutrophication). These six dimensions also provide a framework that can be used to assess existing or planned OA policy and to help guide future policy.

The dimensions span the social and political actions from local to national levels that constitute effective policy commitment to mitigating and adapting to OA risks. We identify countries that are current leaders in each dimension to serve as benchmarks for OA policy preparedness (table 1 and supporting information), and, we use this framework to evaluate the case study of Australia (figure 1, table 1), the country with the world's largest coral reef system. Performance in a given dimension is assessed using standardized indicators outlined below and in table 1 (see supporting information for more detail).

1.1. Climate protection measures

Effective climate policy that decreases carbon dioxide emissions, and thereby, OA [10] is essential to shaping the rational response of a country to OA [9]. Specifically, policy that addresses OA requires addressing CO_2, sulphur oxides (SO_x), and nitrogen oxides (NO_x), which have acidification potential. This dimension can be measured using the international Climate Change Performance Index, which rates the 57 countries and the EU that are responsible for the majority of global emissions against four categories of performance: GHG emissions, renewable energy, energy use and climate policy.

1.2. OA literacy

Enabling evidence-based decision-making about OA requires a foundational knowledge and understanding of the issue across as many sectors of society as possible, which paves the way for more integrated future actions [10]. In this regard, dedicated government infrastructure (e.g. departments that can provide technical assistance, education and outreach) would indicate a degree of progress on this dimension. As well, the incorporation of curriculum material on OA (e.g. within high school teaching schedules) is important in helping develop a better understanding among people and communities of the issue of OA. Non-scientist elected leaders who are willing to take public stances and/or push forward funding or policy pertaining to OA also indicates progress. Rather than develop a data-limited, qualitative index attempting to combine these three elements for many nations, we measure this dimension with evaluation of public climate change awareness and concern as measured by Lee *et al* [11], as a proxy for overall climate literacy.

1.3. Area-based management for climate resilience

Area-based management, including marine parks, reserves, protected areas, and resource management, can build resilience to the effects of ocean warming and acidification [12]. Indicators include the widespread adoption of management strategy documents that explicitly seek to increase resilience to OA and warming, and management programs that measure and report on the effectiveness of existing area-based management measures including deliverables such as vulnerability assessments, adaptive management frameworks, legislative requirements for ecosystem health reporting, and strategic planning documents.

1.4. Research and development

Our understanding of OA and its impacts, as well as solutions, is at a relatively early stage. Therefore, an important step in preparing to respond to OA involves a commitment to research and development [10]. In this regard, building capacity through training programs and international partnerships is also

Table 1. Indicators for each dimension of the ocean acidification (OA) policy preparedness framework. Scoring for each indicator is assessed as a score of 1 equating to no alignment with the indicator and a score of 5 equating to complete alignment with the indicator. For indicators that utilize rankings (e.g. the Climate Protection dimension that references the Climate Change Protection Index), rankings are normalized by assigning a score of '5' to the top 20% of countries and '1' for the bottom 20%. See supporting information for details and additional references.

DIMENSION	INDICATOR	AUSTRALIA CASE STUDY	BENCHMARK
Climate protection measures	1. Ranking in the Climate Change Performance Index	1. Ranked 54 of 57 countries and the EU, placing AU internationally in the rating category of 'very poor' (bottom 20%, Score = 1)	1. Sweden
Ocean acidification literacy	1. Assessment of proportion of population that is aware of climate change and considers it a serious risk, as evaluated by Lee *et al* 2015	1. Ranked 8th of 119 countries (top 20%, Score = 5)	1. Australia
Area-based management for climate resilience	1. Area-based management plans explicitly support resilience to OA	1. Major strategic management documents specifically reference OA and acknowledge risks from climate change: Great Barrier Reef (GBR) 2050 Plan, GBR Outlook Report, GBR Marine Park Authority's Biodiversity Conservation Strategy. Strategies are underpinned by a comprehensive climate change vulnerability assessment and support actions to decrease GHG emissions and build reef resilience (Score = 5)	1. Australia
	2. The effectiveness of area-based management is measured and reported	2. The GBR Outlook Report is a legal requirement of the GBR Marine Park Authority (GBRMPA); this framework reviews risks and evaluates management performance on a 5-yearly cycle. The report is developed from eight specific assessments, which include an evaluation of the current condition and trend of the key values to guide government action (Score = 5)	2. Australia
	3. Programs or mechanisms exist to reduce synergistic stressors (e.g. pollution, overextraction, ecosystem degradation).	3. The GBR Marine Park is one of the oldest and largest marine protected areas in the world, with 33.3% protected. In addition to the legislative requirement to report on ecosystem health (Indicator #2), GBRMPA and partners have a detailed and coordinated approach to managing and reducing stresses of the GBR, including the Reef Water Quality Protection Plan and the Reef 2050 Plan (Score = 5)	3. Australia

(Continued.)

Table 1. (Continued.)

DIMENSION	INDICATOR	AUSTRALIA CASE STUDY	BENCHMARK
Research & Development	1. The existence of training programs on OA	1. One open-call OA training program on the OA-ICC news stream (Score = 1)	1. United States
	2. Dedicated research budget is allocated to understanding and responding to OA	2. 1.79% of AU GDP spent on R&D (2017), ranking 22 out of the 41 evaluated countries and the EU (top 60% of evaluated countries, Score = 3)	2. Israel
	3. The number of publications that a country produces on OA relative to its GDP	3. Ranks 5th of 67 countries, with 641 publications and a GDP of $1.33E + 12USD (top 20% of evaluated countries, Score =5)	3. Monaco
	4. The contribution of OA data to the SDG14.3.1 data portal	4. 15 datasets on SDG14.3.1, with 3,862 observations. AU is the country with the highest number of datasets submitted to the portal (Score = 5)	4. Australia
	5. Involvement in international partnerships focused on understanding and responding to OA (data for this metric are currently sparse)	5. NA	5. NA
Adaptive capacity of dependent sectors	1. Vulnerability of dependent sectors to climate change, including OA, has been assessed	1. Vulnerabilities of reef-dependent sectors to climate change (including OA) have been assessed in both government reports and the peer-reviewed literature. The GBR Vulnerability Assessment and sectoral assessments have provided a strong information base on climate change vulnerabilities as a basis for adaptation planning (Score = 5)	1. Australia
	2. Sector-specific strategies exist to adapt to climate change, including OA	2. Climate change adaptation strategies have been developed for key sectors, including: small & medium enterprise; biodiversity and ecosystems; human health and wellbeing; emergency management; agriculture; built environment and infrastructure; Queensland tourism; and industry and resources (Score = 5)	2. Australia

(Continued.)

Table 1. (Continued.)

	3. Partnerships and networks focused on climate adaptation, including OA, are present, including participation in the OA Alliance and the development of OA Action Plans	3. The GBRMPA developed partnerships and networks focused on climate adaptation during implementation of the 2007–2012 Climate Change Action Plan. These have led to integration of climate change into key partnership programs in the GBR, such as the Reef Guardians program. Internationally, AU is supporting efforts on climate action, including investing $1 billion in climate finance from 2015 to 2020 through aid programs to reduce emissions and build resilience to climate change in developing countries (Reef 2050). AU is not part of the OA Alliance and has not developed an OA Action Plan. (Score = 4)	3. Various (see supp. inf.)
Policy coherence	1. National climate policy is consistent with best-available knowledge	1. In 2017, the AU Government reviewed its climate change policies and found that the existing suite of climate policies remains effective to meet AU's 2030 target and Paris Agreement commitments. However, according to the Climate Action Tracker, AU's climate policies are 'insufficient' in adhering to Paris Agreement goals, and Australia has the second largest CO_2 emissions of the Group of Twenty (G20) after Saudi Arabia (Score = 2)	1. Morocco, The Gambia
	2. Policies across all government departments are consistent with national climate policy (data for this metric are currently sparse)	2. NA	2. NA

an important part of preparing for OA and its impacts. Indicators of performance in this case include the proportion of total research budgets that have been allocated to understanding and responding to OA using data from the Organization for Economic Co-operation and Development, which ranks the 42 member countries with respect to their % of GDP spent on R&D (Note that the development of a metric to track GDP spent specifically on OA R&D would help constrain this indicator); the number of publications on OA that a country produces relative to its GDP, according to the Ocean Acidification International Coordination Center (OA-ICC) bibliographic database (2020) and GDP data from the World Bank (2020); the existence of training programs on OA documented on the OA-ICC news stream 'Courses and training' category; and the contribution of data to the SDG 14.3.1 data portal.

1.5. Adaptive capacity of dependent sectors

Developing the ability to adapt to the consequences of OA requires understanding the vulnerability of dependent sectors and communities, and identification of adaptation options and their benefits and costs [13]. Indicators of performance include the availability of vulnerability assessments for various dependent sectors and sectoral strategies for responding to climate change risks, including OA (i.e. action plans, milestones, measurable outcome indicators), as well as partnerships focused on climate adaptation,

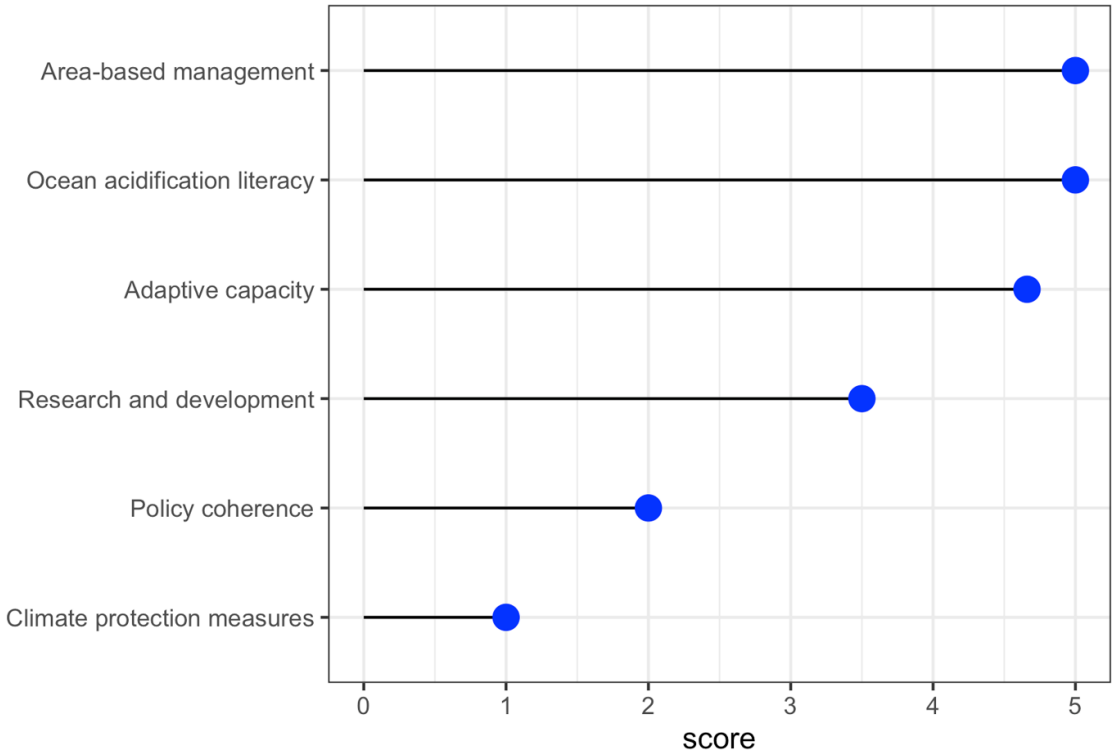

Figure 1. Six key dimensions of policy preparedness for ocean acidification adaptation, as assessed for Australia, the country with the world's largest coral reef system. These dimensions encompass a comprehensive suite of actions that must be taken into consideration to prepare ecosystems and societies for the impacts of ocean acidification. Performance in a given dimension is assessed using standardized indicators as defined in table 1, where 1 is no alignment, 3 is moderate alignment, and 5 is complete alignment. For dimensions with multiple indicators, all indicators are equally weighted (averaged) to calculate the overall dimension index.

including OA, such as participation in the OA Alliance and/or the development of specific action plans on OA (www.oaalliance.org/action-plans).

1.6. Policy coherence

It is vitally important that policy developed for OA is consistent with the best available science, decision-making is evidence-based, and that policies aiming to deal with the issue of OA cannot be offset by other policies [14]. For example, policies supporting expansion of renewable energy to reduce CO_2 emissions would support other policies meant to address OA. This metric weighs data from the Climate Action Tracker, which analyzes the impact of climate policies in 32 countries that produce 80% of global emissions.

These six framework dimensions are broadly illustrative of a government's preparedness to address OA threats because they cover research investment, societal awareness of the issue, and the ability of OA to integrate with other marine policies (e.g. area-based management, climate ambition, adaptation support for dependent communities). These elements are routinely discussed in the policy theory literature as key ingredients required for effective policy [9, 14]. When examined in the policy applications literature [10] these elements also appear as key ingredients leading to success.

2. Case study

2.1. Coral reefs as vulnerable ecosystems

While all marine ecosystems are likely to be affected by OA, some ecosystems such as coral reefs appear to be particularly sensitive to changes to ocean pH and the saturation state of calcium carbonate [7]. Mesocosm studies show that even low levels of additional carbon dioxide cause fundamental changes in ecological structure and function [4]. The combination of ocean warming and acidification projected to occur over the coming decades is extremely likely to eliminate coral reefs as we know them in many parts of the world by 2050 [1]. As the reef framework degrades and net erosion advances, a wide range of negative impacts are likely for coastal human communities [1]. These include reduced food, income and well-being, as well as longer term impacts such as increasing vulnerability of property, safety, and infrastructure as coral reefs become less able to protect coastal areas from storms and waves [1, 7].

We use the above framework to evaluate the case study of Australia, the country with the world's largest coral reef system. Australia is regarded by some as well prepared to address OA, with significant gaps related to overall climate mitigation ambition and policy coherence. Figure 1 shows the overall 'mixed bag' nature of Australia's preparedness—dimensions

where Australia is currently serving as a benchmark for OA preparedness (OA literacy and area- based management), and dimensions which are wholly insufficient to best prepare ecosystems and societies for the impacts of OA (climate protection measures and policy coherence). Data and rationale for Australia's rankings in each dimension indicator are provided in table 1 and the supporting information.

3. Conclusion

The sub-elements of the framework provide a useful rubric for a nation, territory, or province to self-assess policy preparedness for OA. Even just presence-absence information in each of the six dimensions helps identify policy gaps that require additional resources. Where semi-quantitative (e.g. 'limited, moderate, extensive') and/or detailed information for each sub-element is available, it becomes feasible to more finely identify policy gaps. It should be noted that this is a conceptual framework and that given the variability in sources and availability of quality data at this time, care should be taken when making direct comparisons between nations.

The direct relationship between increasing carbon dioxide and the chemical changes to seawater place the attribution of OA to human activities beyond doubt [1]. While current emission reduction commitments to the Paris Agreement signed in December 2015 are admirable, they fall short of achieving the goals set by the international community [15]. Deep and immediate mitigation action is non-negotiable, but we need more. Accelerating OA policy will help prepare ecosystems and societies for the inevitable threats of climate change and OA, helping to safeguard the future. We encourage users to try this interactive and flexible framework to help identify strengths and weaknesses in policy preparedness and to inform prioritization of future OA preparedness endeavors.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Writing—original draft: R A, S F, J P G, G H, O H G, L H, N M, P M Writing—review & editing: R A, S C, S F, J P G, G H, O H G, L H, N M, P M

Conflict of interest

Authors declare that they have no competing interests.

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