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Title: Research priorities for natural ecosystems in a changing global climate

Running head: Research priorities for natural ecosystems

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Abstract:

Climate change poses significant emerging risks to biodiversity, ecosystem function and associated socio-ecological systems. Adaptation responses must be initiated in parallel with mitigation efforts, but resources are limited. As climate risks are not distributed equally across taxa, ecosystems and processes, strategic prioritization of research that addresses stakeholder-relevant knowledge gaps will accelerate effective uptake into adaptation policy and management action. After a decade of climate change adaptation research within the Australian National Climate Change Adaptation Research Facility, we synthesize the National Adaptation Research Plans for marine, terrestrial and freshwater ecosystems. We identify the key, globally-relevant priorities for ongoing research relevant to informing adaptation policy and environmental management aimed at maximizing the resilience of natural ecosystems to climate change. Informed by both global literature and an extensive stakeholder consultation across all ecosystems, sectors and regions in Australia, involving thousands of participants, we suggest 18 priority research topics based on their significance, urgency, technical and economic feasibility, existing knowledge gaps, and potential for co-benefits across multiple sectors. These research priorities provide a unified guide for policy makers, funding organizations and researchers to strategically direct resources, maximize stakeholder uptake of resulting knowledge, and minimize the impacts of climate change on natural ecosystems. Given the pace of climate change, it is imperative that we inform and accelerate adaptation progress in all regions around the world.

Graphical Abstract (see attached file – graphical abstract.pptx)

The capacity to make informed decisions about environmental policy and management in a changing climate relies on monitoring data, scientific analysis, strategic prioritization of new research and the effective synthesis and communication of technical resources and knowledge. Here we identify the most important research required to address stakeholder-relevant knowledge gaps that will increase their capacity to make the best decisions possible to minimize the impacts of climate change on natural ecosystems.

Keywords:

global change biology; adaptation; research prioritization; natural ecosystems; marine; terrestrial; freshwater

One Sentence Summary: Managing the impacts of climate change is limited by current knowledge; we identify the highest priority research questions to fill this information gap.

Main text:

The landmark Paris Climate Agreement emerged from the United Nations Framework Convention on Climate Change COP21 meeting and provided a framework for international action to reduce the impacts of climate change. However, the global emissions reduction pledges and actions made are widely acknowledged as being insufficient to keep global temperatures below a 2 °C limit (Brent, McGee, McDonald, & Rohling, 2018). The World Meteorological Organization (WMO, 2019) recently stated that the last four years have been the hottest on record with an average global increase of more than 1°C relative to pre-industrial levels, currently increasing at approximately 0.2 °C per decade (WMO, 2019). Increases above 1.5 °C will cause widespread and potentially irreversible damage to global ecosystems and biodiversity, and dependent human systems (IPCC, 2018). The catastrophic bleaching of the Great Barrier Reef causing an estimated 50% loss of coral cover and reduced reproductive capacity (Hughes et al., 2017; Hughes et al., 2019), is a stark reminder that the world's ecosystems are already experiencing significant impacts from anthropogenic climate change. There are now thousands of examples of species, habitat and ecosystem processes responding to the changing global climate in all ecosystems, and in all geographic regions [e.g. (Hoffmann et al., 2018; Pecl et al., 2017; Scheffers et al., 2016)]. Traditional conservation and natural resource management practices are widely acknowledged as being inadequate to prevent species extinctions and habitat degradation, and to conserve the ecosystem services on which human well-being depends. It is critical and urgent that we strategically prioritize global research efforts to help meet this challenge and minimize impacts on global biodiversity and ecosystem function.

Minimizing future impacts on biodiversity, ecosystem function and the ecosystem services necessary to human society relies on two, interconnected approaches: (i) Mitigation strategies that reduce greenhouse gas emissions and maintain and/or increase carbon storage, and (ii) Adaptation strategies that aim to reduce the impacts of climate change on natural and human

systems. The Paris Agreement emphasizes the urgent need for a global effort to increase adaptation efforts that enhance adaptive capacity, strengthen resilience and reduce the vulnerability of natural ecosystems. Even if the ambitious mitigation targets of the Paris Agreement are achieved, many species and natural systems will still require significant adaptation efforts, as impacts are already widespread and significant, well below the 1.5 ° or 2 °C warming targets (Figure 1).

Effective human-mediated adaptation practices are often limited by the lack of knowledge to make informed decisions, presenting an enormous global challenge to environmental management and policy across all ecosystems and societies. Therefore, there is an urgent need for carefully targeted investment in adaptation underpinned by robust vulnerability assessments and adaptation research to inform decisions, policy and actions (Moss et al., 2013; Schindler & Hilborn, 2015). However, there are technical, economic and social barriers and challenges to adaptation in all sectors (e.g. Alistair J Hobday, Chambers, & Arnould, 2015; Lynham et al., 2017). We need to prioritize where scarce resources should be targeted to provide the research, knowledge and societal capacity to make informed decisions about the management of natural ecosystems and the invaluable services they provide to human society. Meeting this challenge and managing natural ecosystems in a changing climate requires: flexible, proactive policy and management approaches informed by existing knowledge, ongoing long-term environmental monitoring and enhanced by strategically prioritized research to fill knowledge gaps; and synthesis and communication of the science to relevant stakeholders (Figure 2). Progress in developing adaptation plans varies around the world, and lessons from regions should be exchanged to enhance the progress of new or re-energized adaptation planning efforts.

The Australian Government established the National Climate Change Adaptation Research Facility (NCCARF) in 2008 to identify and facilitate the research needed to underpin effective decision-making for climate adaptation (www.nccarf.edu.au). National Adaptation Research Networks were developed under the auspices of NCCARF for eight sectors including marine, freshwater, and terrestrial ecosystems. Each network was deliberately constructed to include a representative cross-section of researchers and stakeholders that included environmental management practitioners and policy makers within national, state and local governments, resource management groups, community groups, international and regional NGOs, funding agencies and businesses. In the second phase of the NCCARF

process (2013-2016), the three ecosystem networks (i.e. marine, freshwater and terrestrial) were consolidated into a single Natural Ecosystems network with over 2000 members across Australia, comprising 48 % scientists /researchers and 52 % stakeholders. All network outputs and activities involved stakeholder participation and included >50 stakeholder consultation workshops, >40 science workshops, major involvement in 15 scientific conferences, more than 350 presentations, >200 scientific publications and many other outputs aimed at informing climate change adaptation responses and policies. Comprehensive literature reviews on impacts and adaptation options within each of the three ecosystems were followed by extensive stakeholder engagement across Australia to ascertain the knowledge required by stakeholders to inform policy and management decisions. Each network then produced a National Adaptation Research Plan (NARP) to identify ongoing knowledge gaps, guide research to fill these gaps, strengthen linkages between researchers and stakeholder/end-user groups, reduce duplication, and maximize return on public investment in research (e.g. Ling & Hobday, 2018). The NARPs were updated twice between 2010-2017: for more detail see the individual NARPs (Capon et al., 2017; Hobday et al., 2017; Williams et al., 2017) and NCCARF website resources.

Adaptation to a changing climate is critical for the conservation of natural ecosystems and the preservation of links between ecological and socio-economic systems (Figure 1c) (Pecl et al., 2017). Therefore, increasing our knowledge about effective adaptation strategies is essential. However, research to provide this knowledge must be strategically prioritized to maximize cost-effectiveness and address the needs of environmental managers and policy makers. So where should governments and funding agencies strategically direct resources to address this issue? To answer this question, we synthesize a decade of climate adaptation research in Australian marine, freshwater and terrestrial ecosystems, and identify the key, globally-relevant priorities for ongoing research. These priorities have been informed by the extensive stakeholder consultation process described above. Grouped within four major research themes, we suggest 18 Research Priorities based on their significance, urgency, technical and economic feasibility, existing knowledge gaps, and the potential for co-benefits across multiple sectors (Table 1 and supplementary text). These priorities provide a unified guide for policy makers, funding organizations and researchers to strategically direct resources, maximize the uptake of the resulting knowledge and minimize the impacts of climate change on natural ecosystems.

The 18 Research Priorities were identified by initially collating and classifying research priorities identified within each of the three latest editions of the National Adaptation Research Plans in a workshop. The overall synthesis and assessment process consisted of four steps (below) with steps 2-4 being completed in a workshop by the authors as representative experts from each ecosystem network, all with previous high-level involvement in producing the three separate National Adaptation Research Plans:

1. Nine years of extensive stakeholder consultation across each of the three ecosystem networks resulting in the three ecosystem-based Australian National Adaptation Research Plans (NARPs);

2. Synthesizing the research questions from each ecosystem NARP into a single set of high-level questions relevant to all natural ecosystems;

3. Selection of six criteria for ranking and prioritizing research based on best practice approaches aimed at facilitating the effective uptake of research prioritization into policy (Rudd, 2011) and factors identified by the extensive stakeholder consultation processes conducted within the NCCARF over the previous 10 years (Capon et al., 2017; Hobday et al., 2017; Williams et al., 2017). We then applied a scoring system designed to capture the likely overall impact/benefit from investment in each question based on six criteria (significance, urgency, technical and economic feasibility, existing state of knowledge, and benefits to multiple sectors), and;

4. Ranking each synthesis research question for each ecosystem based on the prioritization criteria. Summarized results are presented in Table 1 with more detailed descriptions and full scores in Supplementary text and table.

The Priority Research questions identified can be categorised into four broad themes:

(1) General goals, policy and implementation strategies for conservation and resource use

Climate change presents an enormous challenge to conservation practice, not only because of the biophysical impacts but because it requires reframing the general principles that underlie conventional approaches. We need to develop guiding principles for conservation based on a fundamentally different paradigm of managing

ecosystem change that emphasizes a proactive (predictive) and spatially/temporally dynamic approach, rather than the traditional, reactive paradigm that relied largely on managing existing threats and protecting high value areas.

(2) Integrated (ecosystem-based) management and adaptation

Traditional protected area strategies are no longer sufficient for the conservation of biodiversity across diverse and multi-use land, water and seascapes. Sustainable management of natural ecosystems in the face of climate change will be enhanced by integrated approaches that incorporate activities such as biodiversity conservation, carbon storage/emissions abatement and sustainable resource use. There is an urgent need for increased understanding of how landscape configuration can be managed to optimize biodiversity conservation, while simultaneously promoting productivity in sectors such as agriculture, aquaculture, fishing and tourism.

(3) Managing threats and stressors

Synergistic interactions between climate change and other human pressures likely pose the most important threats to global biodiversity. Understanding the impacts of such interactions across multiple scales will assist in allocating resources between ameliorating existing stressors and implementing new adaptive strategies that specifically address climate change (e.g. species translocations). The best solution may not be the optimum for any individual stressor but rather one that maximizes the benefits across multiple stressors.

(4) Managing natural assets and dependent human systems

Public support is often most strongly aligned with protecting particular iconic species and, as a result, much conservation effort and adaptation action has been driven by species-level concerns important for a subset of stakeholders. In contrast with the previous themes, therefore, this area encompasses research questions regarding the management of specific biodiversity assets, primarily species, including those that support human activities, such as fishing and tourism.

Synthesis across the three ecosystem realms revealed strong commonalities in knowledge gaps and research prioritization (Table 1; see Supplementary Table S1 and text for more detail on the comparison across ecosystems). Of the 18 Priority Research questions, the highest priorities identified through our assessment process were: 1) social barriers to

adaptation; 2) transformational adaptation in management, planning, policy, law and institutional structures to enable processes that are flexible, dynamic and proactive; 3) extreme events and their thresholds of impact 4) vulnerability of species, processes, services and ecosystems; 5) long-term environmental monitoring systems; and, 6) connections across ecosystems, especially with respect to integrating adaptation and mitigation actions.

Generally, there was close agreement across the different ecosystem realms about the highest priority research questions (see supplementary Table S1 for individual scores for each realm). There were, however, a few noteworthy differences among realms. For example, addressing social and institutional changes in marine systems was perceived as a lower priority than in the other two realms as it has already been investigated to a greater degree in marine management and policy (e.g. Creighton, Hobday, Lockwood, & Pecl, 2016). There was also a greater perceived priority for strategic selection of protected areas to increase ecosystem resilience within the terrestrial realm. The importance of environmental monitoring systems was ranked as being of highest importance in all three realms; the only factor that lowered the overall score of this priority was the relatively high economic costs involved, thereby lowering the economic feasibility score.

An example of the successful outcomes possible from combining stakeholder needs, biodiversity analyses and networking is provided by the Queensland Government Landscape Resilience program (Vanderwal, Williams, Atkinson, & Reside, 2015; Williams, Falconi, Scheffers, 2015). As described in Figure 2, long-term research and monitoring, data compilation, synthesis and analysis, strategic research prioritization, policy and conservation goals were explicitly linked to stakeholder needs via the NCCARF network and collaboration with the Queensland State Environment Department to identify locations with the highest potential to protect the most species into the future. The Queensland Government subsequently created more than 10 new National Parks in an ongoing program aimed at maximizing future landscape resilience under a changing global climate. This outcome was only possible due to the increased capacity within the Queensland Government to make informed decisions based on the integrated approach described in Figure 2 and facilitated by the National Climate Change Adaptation Research Facility and biodiversity research carried out within the Australian Wet Tropics World Heritage Area (Williams & Falconi, 2015).

Our synthesis demonstrates strong commonalities across the different ecosystem realms in the knowledge gaps we need to fill to advance climate change adaptation in natural systems. This work represents the culmination of a substantial investment across the natural ecosystem science, management and policy sectors of Australia, and can serve as a model for other regions tackling ecosystem adaptation in a changing climate.

Summary

There is clear evidence of climate-driven change in all ecosystems globally (Pecl et al., 2017; Smale et al., 2019) and an urgent global need for strategic research that supports policy and environmental management to facilitate effective adaptation (Moss et al., 2013; Schindler & Hilborn, 2015). This synthesis of the three ecosystem-based National Adaptation Research Plans in Australia and assessment of the highest priorities across ecosystems clearly demonstrate strong commonalities. This analysis has filtered, refined and synthesized existing knowledge about adaptation research priorities for natural ecosystems, and then reassessed this knowledge based on a decade of research and shifting societal priorities. Research prioritization is an important strategic step to enable governments, other research funding agencies, and research providers to advance knowledge that targets the needs of stakeholders in the most efficient manner possible. The NCCARF effort in Australia provides a valuable model that can be applied globally to formulate policy, strategically direct research effort, and maximize the adaptive capacity of ecosystem managers. Although this synthesis has an Australian context, the process of research prioritization and the high-priority research questions identified here are globally relevant. Addressing these priority questions in the next decade is critical, particularly given the accelerating impacts predicted above 1.5 °C and the increasing likelihood global warming will significantly exceed the Paris target of +2 °C this century.

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Table 1. Priority research themes and questions on climate change adaptation in natural ecosystems based on a synthesis and expert assessment of Australia's National Adaptation Research Plans for terrestrial, marine and freshwater ecosystems. These questions represent the highest priority research topics relevant to all three natural ecosystems. Rankings were based on six criteria: the significance of the research, the existing knowledge gap, technical and economic feasibility, urgency, and potential for co-benefits across multiple sectors. Each question was ranked for each criterion as low (1), medium (2) or high (3) priority within each separate ecosystem realm (terrestrial, freshwater and marine) and then summed (max score = 9). For detailed descriptions of each research question and individual scoring for each question and criteria, see Supplementary Table S1 and Supplementary text.

Research Themes	Priority Research Questions/Topics	Significance	State of Knowledge	Feasibility - Technical	Feasibility - Economic	Urgency	Co-benefits	Priority Score
1. General goals, policy and implementation strategies for conservation and resource use	**1. What are the main social barriers and opportunities for effective adaptation and how do we overcome them?**	8	8	9	9	8	9	**51**
	2. How do we ensure conservation and natural resource management goals, policies and practices are flexible, dynamic and proactive in the face of a rapidly changing world?	9	7	9	9	8	8	**50**
	3. How can adaptation and mitigation strategies be optimized to include the connections and synergies between terrestrial, freshwater	9	7	6	8	8	9	**47**

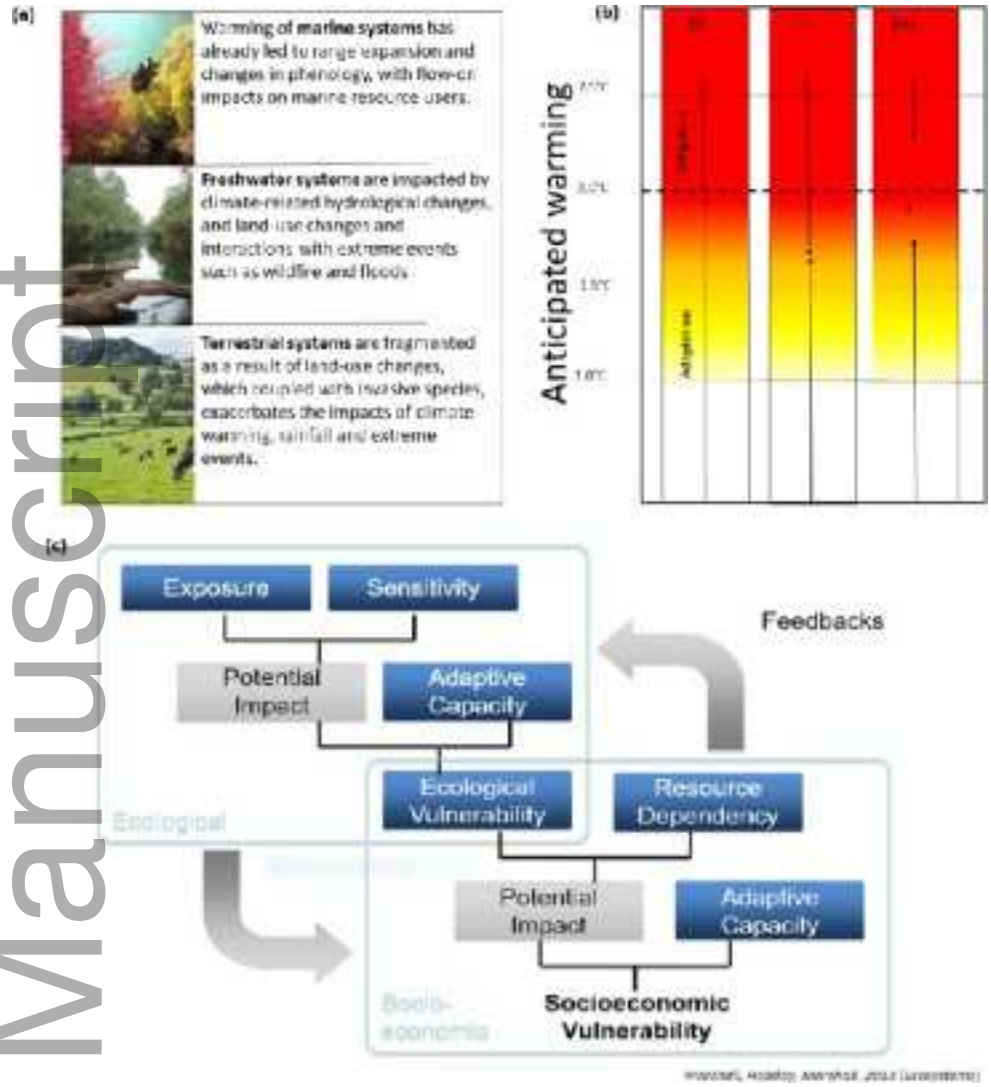
	and marine ecosystems?							
	4. How should we ensure that the existing legal, policy and institutional architecture is aligned for more effective and flexible management of ecosystems, natural resources and production systems (agriculture, fisheries, aquaculture)?	7	4	8	9	8	8	**44**
	5. How can we better communicate the importance of effective adaptation aimed at protecting the values and services of natural ecosystems?	9	5	7	6	8	9	**44**
	6. How can adaptation planning be embedded within, and take advantage of, major human demographic and economic trends?	6	4	9	9	6	6	**40**
2. Integrated (ecosystem based) management and adaptation across diverse and multiuse land, water and seascapes	**7. What conceptual models and long-term observation/monitoring systems are needed to facilitate effective and dynamic natural resource management?**	9	9	9	3	8	9	**47**
	8. How can emission reduction initiatives be designed to enhance biodiversity benefits and ecosystem services?	8	7	7	6	9	9	**46**
	9. How can we incorporate climate change adaptation into on-ground natural resource management practices?	8	6	7	6	7	8	**42**
	10. What principles should guide ecosystem-based adaptation and the design of land, water and seascapes?	9	7	5	6	6	8	**41**
	11. How should new protected areas be selected to maximize the resilience of ecosystems and natural resources?	5	7	9	9	4	5	**39**

	12. What are the implications of novel ecosystems for conservation and natural resource management?	5	6	3	6	3	3	**26**
3. Managing threats and stressors	**13. How can we identify critical biological thresholds that may be exceeded during extreme events to design effective adaptation strategies?**	9	9	7	6	9	9	**49**
	14. What will be the synergies, interactions and cumulative impacts of existing stressors and climate change on natural ecosystems and what are the implications for managing ecosystems and natural resources?	9	6	5	3	9	9	**41**
4. Managing natural assets and dependent human systems	**15. How do we identify and prioritize species/communities that should be the focus of investment in climate change adaptation?**	9	5	9	9	8	7	**47**
	16. How do we optimize cost-benefit analyses of adaptation actions aimed at protecting biodiversity assets?	9	9	6	5	8	6	**43**
	17. How should current on-ground management actions for protecting priority species / communities and managing problem species be modified in the context of a rapidly changing climate?	6	5	5	7	8	8	**39**
	18. What opportunities are there for human dependent systems to adapt to climate change effects through changing focal species and management regime, risk management, or industry diversification, relocation or divestment?	9	5	5	5	6	9	**39**

Figure Captions

Figure 1. Reducing the already evident impacts of climate change on natural systems (A) will require mitigation efforts that limit the warming (B), and adaptation efforts that seek to reduce the exposure and sensitivity and/or increase the adaptive capacity of natural systems and decrease the resource dependency and/or increase the adaptive capacity of the linked human component of natural systems (C). If mitigation efforts achieve the 2°C limit, adaptation efforts will still require significant effort (Bi); if warming is kept below 2°C, less adaptation will be required (Bii), but if mitigation efforts are unsuccessful with regard to the target, more interventionist adaptation will be needed, and there may be a gap (Biii). Colour bars in B represent the vulnerability of natural systems to global warming, modified from IPCC (IPCC, 2007) Fig 11.4.

Figure 2. Informed adaptation and capacity building leads to better policy and management. Diagrammatic representation of the essential components of adaptation that need to be integrated for effectively informing policy makers and environmental managers concerned with avoiding species extinctions and habitat degradation. Long-term monitoring is vital for providing spatial and temporal data on species distributions and abundance, environmental conditions and trends over time; Biodiversity Science encompasses many aspects of describing and understanding the drivers of spatial patterns of biodiversity, providing knowledge on the spatial location of potential refugia, significant biodiversity hotspots, and geographic patterns of vulnerability; Research Facilitation includes many aspects of strategic prioritization and allocation of funds informed by stakeholder needs, thereby maximizing uptake of the research; Information Exchange increases the speed of adaptation knowledge uptake and communication of successful strategies to other stakeholders while also decreasing duplication of research and increasing the effectiveness of funding; Synthesis and Meta-analysis emphasize the use of existing knowledge and the integration of data sets, thereby increasing the power of subsequent analyses and the overall robustness of the knowledge.



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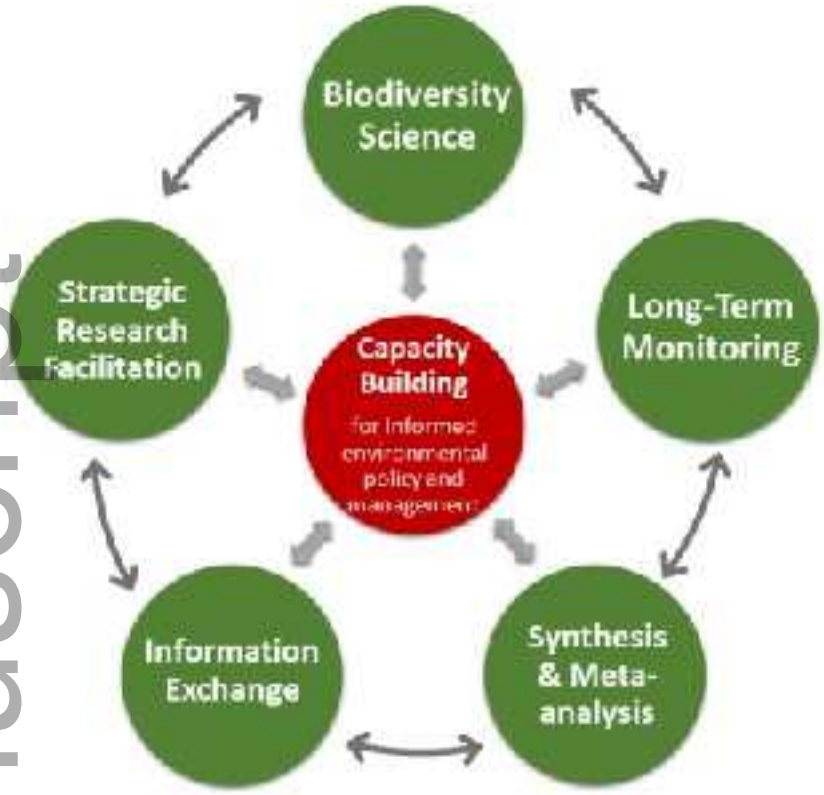

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