Trends in Ecology & Evolution

CellPress REVIEWS

Opinion

Securing a Long-term Future for Coral Reefs

Ove Hoegh-Guldberg,[1,2,3,*] Emma V. Kennedy,[1] Hawthorne L. Beyer,[1,4] Caleb McClennen,[5] and Hugh P. Possingham[1,4,6]

Rapid ocean warming as a result of climate change poses a key risk for coral reefs. Even if the goals of the Paris Climate Agreement are achieved, coral reefs are likely to decline by 70–90% relative to their current abundance by mid-century. Although alarming, coral communities that survive will play a key role in the regeneration of reefs by mid-to-late century. Here, we argue for a coordinated, global coral reef conservation strategy that is centred on 50 large (500 km^2) regions that are the least vulnerable to climate change and which are positioned to facilitate future coral reef regeneration. The proposed strategy and actions should strengthen and expand existing conservation efforts for coral reefs as we face the long-term consequences of intensifying climate change.

Highlights

Severe degradation of coral reefs in recent decades has been driven by a range of threatening processes including climate change. Ocean warming is expected to have further severe impacts on reefs unless global warming is restrained well below 2°C (the goals of the Paris Agreement).

Not all coral reefs are equally at risk from climate change, however, suggesting the potential for identifying reefs for conservation action that are less vulnerable to climate change and which may be best positioned for regenerating other degraded reefs in the future.

There is uncertainty in future conditions. Variance reduction methods from finance (e.g., modern portfolio theory) can be applied to conservation planning to identify a portfolio of coral reefs for which the risk of widespread failure across the portfolio is minimised.

Long-term, risk-sensitive planning in the context of the uncertainty of projected climate impacts complements existing conservation strategies.

Coral Reefs

Coral reefs provide habitat to over a million species as well as essential ecosystem services (e.g., food, coastal protection) to hundreds of millions of people throughout the tropics and subtropics [1,2]. Despite their importance, coral reefs are in rapid decline, with the rate accelerating for many coral reefs over the past decade (e.g., Great Barrier Reef, [3]). Human impacts such as fishing pressure, coastal development, and pollution are combining with rising ocean temperatures to push reefs increasingly into states typified by low coral abundance, reduced biodiversity, and degraded ecosystems services [1,2]. While all threats facing coral reefs need addressing, those associated with global ocean warming are the most serious, with the near total loss of coral reefs across the planet expected by midcentury under current greenhouse gas emission projections [3–5]. Within this context, reducing the impact of local threats has the potential to build much needed resilience for coral reefs as they face escalating threats from global climate change.

Paris to the Rescue

The United Nations Framework Convention on Climate Change (UNFCCC) and its 21st Conference of the Parties (COP21) agreed to hold 'the increase in the global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C above preindustrial levels' [6]. To date, 180 of the 197 parties have ratified the **Paris Agreement** on climate change. This agreement is founded upon a scientifically based target under which relatively stable ocean conditions may be achieved by midcentury [4]. While current pledges to reduce emissions by the world's nations fall short of what is required to achieve the goals of the Paris Agreement [7], there is considerable hope that the international community will continue to work together to ramp up the emission reduction ambitions of its member states over the coming years.

While the Paris Agreement was an impressive political achievement, average planetary surface temperature is expected to increase by another 0.5°C, putting further strain on already stressed natural and human systems. Under optimistic projections, the trend of increasing heat stress may render approximately 70–90% of the current distribution of coral

[1]Global Change Institute, University of Queensland, St Lucia 4072 QLD, Australia
[2]School of Biological Sciences, University of Queensland, St Lucia 4072 QLD, Australia
[3]ARC Centre for Excellence for Coral Reef Studies, University of Queensland, St Lucia 4072 QLD, Australia
[4]ARC Centre for Excellence in Environmental Decisions, University of Queensland, St Lucia 4072 QLD, Australia
[5]Wildlife Conservation Society 2300 Southern Boulevard Bronx, NY 10460, USA

 https://doi.org/10.1016/j.tree.2018.09.006

reef habitat unsuitable for most corals [8–10]. Failure to achieve the Paris Agreement, however, will see the near total loss of coral reefs for the foreseeable future [4]. Pressures from global climate change add to the pressures from local factors such as coastal development, pollution, and overfishing to seriously threaten the viability of coral reefs.

[6]The Nature Conservancy, 4245 North Fairfax Drive, Suite 100, Arlington, VA 22203-1606, USA

*Correspondence: oveh@uq.edu.au (O. Hoegh-Guldberg).

Here, we argue for a global, long-term strategy for protecting coral reefs that are both least vulnerable to climate change, and which are well positioned to facilitate the regeneration of many coral reefs later this century (Box 1 and Figure 1). Recognizing that the restoration of coral reefs may make sense at some scales of intervention [11–13], we argue that the future for coral reefs depends mainly on the success of these approaches being used together with large scale conservation initiatives (Box 2). To ensure that coral reefs persist beyond midcentury, strengthened conservation policies [14], innovative and expanded financing [15,16], and increased on-the-ground capacity will all be required [17].

A Glass 10–30% Full: Which Reefs Are Best for Regenerating Coral Reef Ecosystems?

Given limited resources, effective conservation policy requires both intervention and geographic prioritization [18,19]. Here, we describe a global strategy (see Figure I in Box 1) that focuses on identifying well-connected coral reefs that have the best chance of surviving projected climate change along a ‘well below 2°C’ pathway, as defined in the Paris Agreement (COP21 2015). Working under the assumption that the goals of the Paris Agreement will be achieved, these reefs (Figure 1) are likely to play important roles in facilitating the persistence of corals as global average temperature increases by another 0.5 °C, and the subsequent regeneration of coral reefs in the broader context as ocean temperatures stabilize. Thus, ensuring that the array of non-climate change related threats do not degrade or eliminate these reefs over this time period is of critical importance. The questions underpinning policy development then become: how does one objectively identify coral reefs that are relatively less vulnerable to climate change yet are better positioned to facilitate the regeneration of other reefs in the future? And, on the conservation side, where must we carry out actions that mitigate near-term threats (Box 2 and Figure 2), especially in the context of uncertainty?

Box 1. Using MPT to Inform Conservation

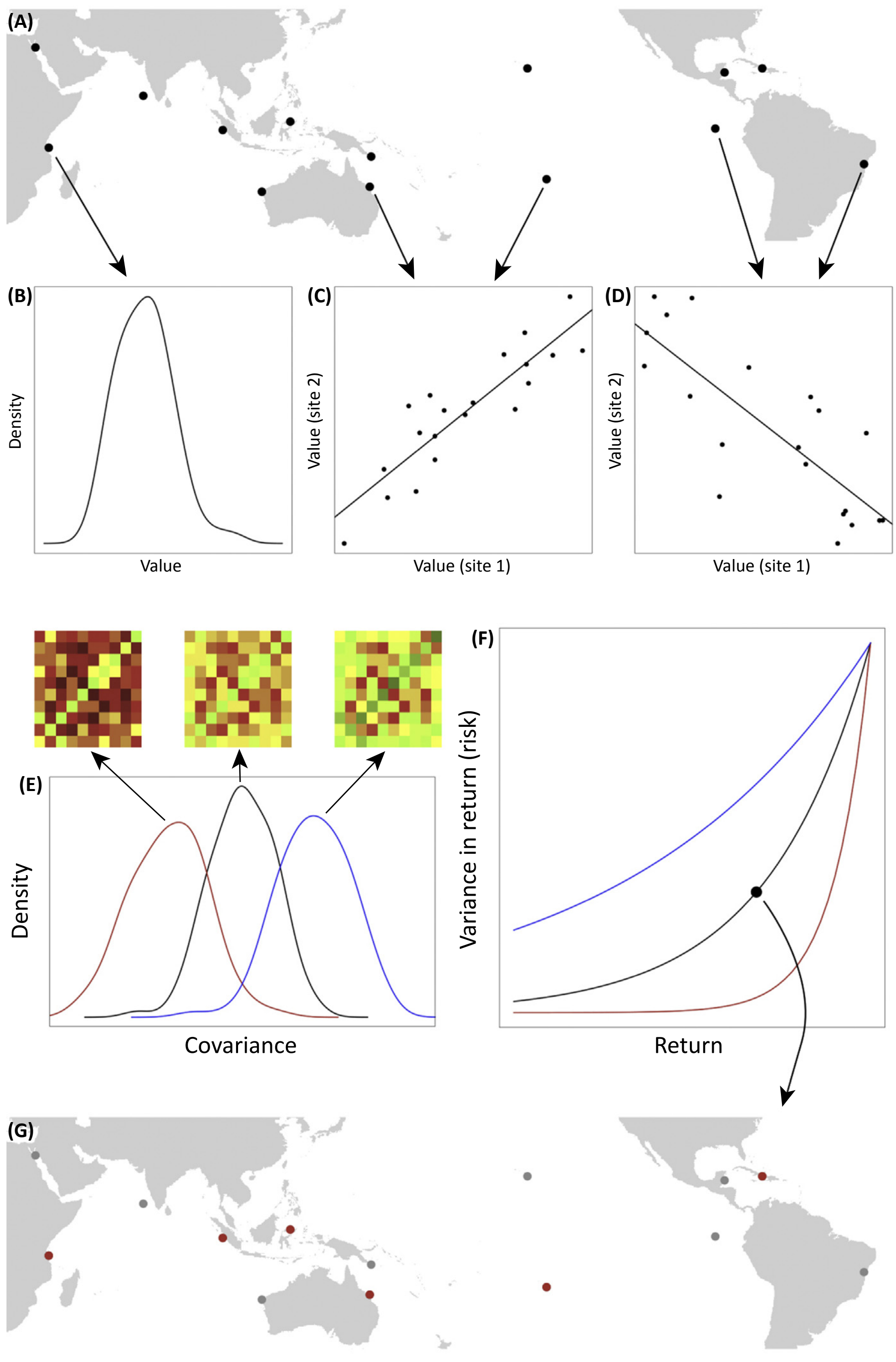
MPT [15] is a mathematical approach for building portfolios of assets that maximise the expected return for a given level of risk. The idea is built around the concept that the risk to an asset should be assessed in the context of the overall risk and return of all assets in a given portfolio. Variance-reduction methods are widely used in the financial sector, and MPT was part of the work for which Harry Markowitz received the 1990 Alfred Nobel Memorial Prize in Economic Sciences.

Conservation planning is also fundamentally concerned with investing limited resources to achieve conservation outcomes (returns) while minimising the risk of failure of those projects. In the case of coral reef conservation, uncertainty in projected long-term conservation outcomes is driven by variation in estimates of climate change impacts. MPT provides a risk-sensitive framework for conservation planning that explicitly accounts for the covariance in expected outcomes among planning units (investment opportunities).

Beyer *et al.* [20] applied MPT to the problem of selecting 50 coral reef areas at a global scale (Figure I) that are among the least vulnerable to climate change impacts, and which have the potential to also foster regeneration in other areas via larval dispersal. There are often complex impacts of climate on biological systems that are difficult to capture with a small number of metrics. Beyer *et al.* used 174 metrics to quantify past and projected ocean warming impacts and risks of cyclone damage, as well as connectivity to other reefs, thereby ensuring that the solution is robust across a wide range of measures of climate change impact. They found substantial opportunity to reduce risk in the portfolio, while sacrificing only relatively small amounts of performance in expected conservation outcomes. MPT and other variance reduction methods provide important opportunities for improving long-term conservation planning to ensure it is more robust to uncertainty arising from climate change.

Trends in Ecology & Evolution

Cell Press REVIEWS



Trends in Ecology & Evolution

Figure I. Building a Global Portfolio for Coral Reef Conservation in a Time of Rapid Environmental Change. (A) The problem is to identify a subset of sites (black dots) within which conservation actions will be focused. (B) There is, however, uncertainty in the expected future value of each site arising from climate change and other biophysical processes. Moreover, (C) some of the sites have correlated values that behave similarly in the context of climate change,

Glossary

Anthropocene: the geological age in which people became the dominant influence on the climate, biosphere, and environment.

Assisted evolution: activities that accelerate the rate of naturally occurring evolutionary processes with the aim of introducing beneficial traits into a population, such as adding heat-tolerant varieties of corals to natural populations to speed up ~~shift and~~ overall heat tolerance. Sometimes referred to as human-assisted evolution.

Bioclimatic units (BCUs): areas defined in the current publication as containing approximately 500 km^2 of coral reefs, which have lower vulnerabilities to heat stress (coral bleaching and mortality) and storms, and are well-connected to surrounding systems.

Coral reef ecosystems: shallow water reefs (down to 40 m) that are dominated by scleractinian (reef building) corals that are host to symbiotic dinoflagellate algae (genera *Symbiodinium*), and which typically support a highly diverse community of species.

Global Environment Facility: international partnership of 183 countries aimed at addressing global environment issues while supporting national sustainable development initiatives.

Green Climate Fund: an international fund established within the framework of the UNFCCC to assist developing countries in adaptations mitigation practices aimed at reducing climate change.

International Year of the Reef (IYOR): the International Coral Reef Initiative declared 2018 as the third International Year of the Reef with the aim that actions on local and global threats to coral reefs are accelerated.

Low-impact aquaculture: aquaculture with a reduced ecological footprint from waste production, sustainable sourcing of feedstocks, and prevention of genetic pollution from escaped aquaculture stocks (e.g., introduced fish, crustaceans, disease).

Nationally determined contributions (NDCs): voluntary commitments by the international community to reduce greenhouse

Box 2. Accelerating Conservation Action within BCUs

Developing conservation plans within the selected BCUs begins with a participatory site assessment to identify actions that are likely to deliver conservation returns in the near to medium term. This assessment should be integrated into local planning processes and institutions where appropriate, but at minimum should provide for: (i) threat assessment, (ii) Institutional capacity assessment, (iii) monitoring and evaluation (M&E), and (iv) policy development and implementation. Protocols for site assessments have been developed by a variety of sources (METT, NOAA, SocMon) [33–35].

Threat assessments are required for all locally relevant drivers, including, but not limited to: fisheries, coastal development, land-based pollution, and climate change. The development of solutions might include: expanding habitat conservation measures (e.g., marine protected areas, multi-use marine parks), regulating and rebuilding fisheries, reducing sedimentation and nutrient run-off, or rehabilitating coral reefs following extreme events such as storms and heat waves.

Institutional capacity assessments should evaluate locally appropriate institutions relevant to governance, financial resources, training and education, technical capacity for implementation of conservation measures, and available social and natural scientific information. This capacity assessment will uncover key pathways to deliver threat mitigation strategies, such as new financial mechanisms to improve erosion control in upland agriculture, capacity building programs for park or fisheries enforcement officers, community engagement to increase participation in reef governance, and technical training or data collection.

M&E systems are critical to the long-term adaptive management and tracking of changes both within and across BCUs. Initial participatory site assessments should identify existing M&E systems or build a baseline for future evaluations. In this regard, there are growing opportunities for technologies, from automated underwater vehicles, low-altitude drones, and remote sensing (coupled with AI) to strengthen and expend M&E capabilities within many BCU regions [36]. The combined assessment of threats, institutional capacity, and M&E should conclude with a gap and opportunity analysis that identifies key areas for local and global investment to secure the long-term viability of each BCU.

Policy development and implementation: facilitating the development of policy aimed at creating effective and lasting regulatory mechanisms is important for the long-term sustainability of coastal resources such as coral reefs. Alongside leadership,and legislative gap analysis, policy development across the many countries involved has the potential to deliver benefits of scale and experience. Adaptive policy development is needed in response to the strong drivers of change likely to be experienced over the coming decades and century.

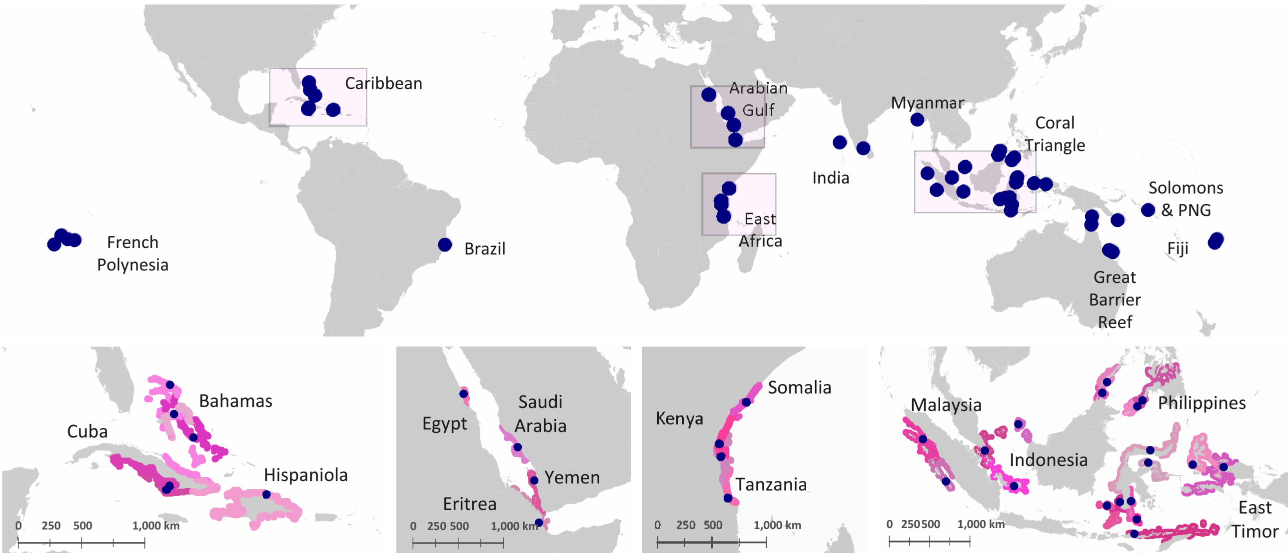
A recent study [20] applied modern portfolio theory (MPT, Box 1, [21]) to solve the problem of identifying a portfolio of reefs (Figure 1) that has a high probability, as a set, of surviving climate change while having a good capacity to repopulate other reefs over time. MPT is a mathematical approach for identifying an optimal portfolio of assets, such that the expected return on investments is maximized for a given level of risk. Up until recently, MPT has not been applied to spatial planning problems, and not at a global scale [22,23]. In the context of long-term conservation planning, risk arises from the substantial uncertainty in the projection of future climate conditions. By accounting for the covariance in conditions among sites, MPT facilitates the selection of a portfolio of sites or **bioclimatic units (BCUs**, Figure 1**)** that are likely to provide good return on investment, with a lower risk of catastrophic loss across the entire

gas emissions as part of the UNFCCC Paris Climate Agreement.
Paris Agreement: also called the Paris Climate Agreement, the part of the United Nations Framework Convention on Climate Change (UNFCCC) that is focused on reducing climate change through greenhouse gas emissions mitigation, adaptation, and finance mechanisms, with a review cycle starting in the year 2020.
Sustainable development goal (SDG): a universal call to action to end poverty, protect the planet's ecosystems, and ensure that all people enjoy peace and prosperity. SDG 14 focuses on the ocean.
Sustainable fisheries: those that are harvested at a sustainable rate, where the fish stocks size do not decline over time because of harvesting. Maximum sustainable yield is central to this concept and represents the largest yield (or catch) that can be removed from fishery without impacting stock size.

(D) while others are uncorrelated or even negatively correlated. (E) The covariance among sites can vary among different applications and contexts. The distribution may be dominated by uncorrelated or negatively correlated values (red line), by positively correlated values (blue line), or a more even mix (black line). The objective is to select a portfolio of sites that maximises expected value (returns). But selecting sites that are correlated is risky, because if one performs poorly, many or all may also perform poorly. Modern portfolio theory provides a way of maximising returns while also reducing risk by accounting for covariances in the selection of sites. (F) The shape of the trade-off between risk and return will be determined by the return values and covariance among sites. If there are many positively correlated sites, this implies relatively few opportunities for selecting negatively correlated sites, and the potential for risk reduction is modest (blue line). Conversely, if there are many negatively correlated sites, the potential for risk reduction will be much stronger (red line). (G) The decision maker must decide what a reasonable balance is between risk and return (black dot), which corresponds to a specific selection of sites.

Trends in Ecology & Evolution

Cell Press REVIEWS



Trends in Ecology & Evolution

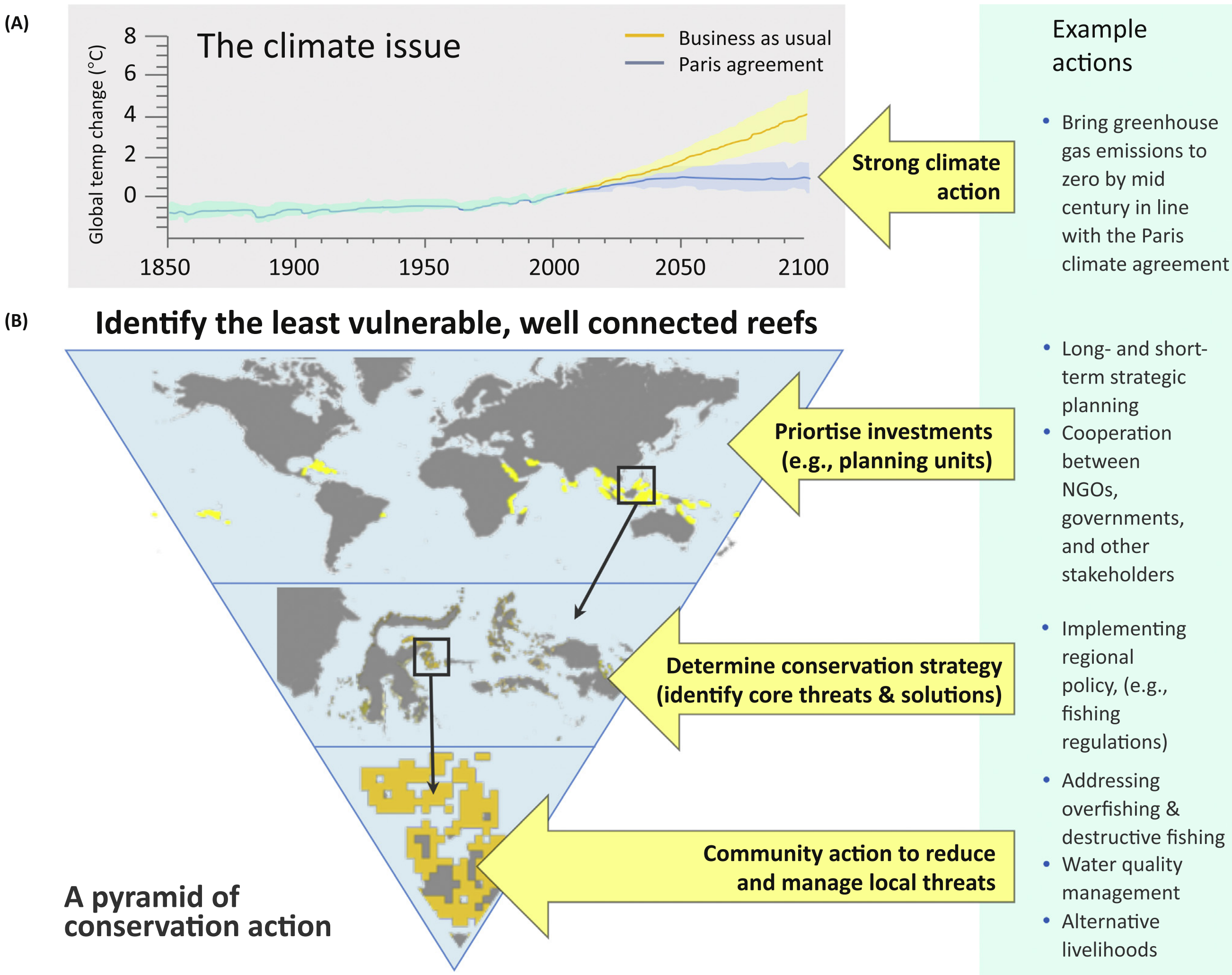
Figure 1. A Global Coral Reef Conservation Portfolio. Location of the 50 coral reef regions or bioclimatic units (BCUs) identified using a modern portfolio theory approach to balance expected conservation returns and risk of poor performance across the portfolio (Box 1). Reef symbol sizes have been exaggerated to improve visibility. The 'Coral Triangle' consists of locations primarily falling with the waters of Indonesia, the Philippines, Malaysia, Papua New Guinea, Solomon Islands, and East Timor. The Red Sea includes reefs falling primarily within the waters of Egypt, Sudan, Saudi Arabia, Eritrea, and Yemen. Further details and on-line resources around the portfolio of BCUs are provided by Beyer *et al.* [21].

portfolio. MPT was used in this particular study to optimize the selection of a portfolio of 50 BCUs with respect to the reduced exposure of BCUs to thermal stress in the past and future (i.e., mass coral bleaching and mortality) and storm damage, while also having a high degree of larval connectivity to other coral reefs. The large size of the 50 BCUs (500 km^2) reduces the inherent vulnerability associated with selecting small areas, while providing flexibility in the potential conservation interventions that could be implemented given differences in the range, scale, and the immediacy of threats (Figure 2).

Risk-sensitive, spatially explicit decision support tools like this can assist decision-makers in identifying objective and transparent solutions (and hence policy) for conservation problems. Importantly, decision support tools like MPT are designed to inform but not prescribe solutions. It is generally not possible to incorporate all dimensions of a problem into a single decision support tool in all but the simplest of problems. For example, some of the BCUs identified by Beyer and colleagues [20] occur in places where governance or local socio-economic conditions for improved conservation are not optimal. In other cases, highly valuable sites may also be too small to be prioritized in a global-scale analysis, but clearly warrant conservation action. Hence, the translation of a theoretically optimal portfolio to one that will be practical to implement requires adjustments based on local conditions and evidence.

Selected Reefs; What Next?

Innovative science, increased global awareness, political commitment, and resourcing of a global response to the threat that climate change poses to coral reefs are necessary but not sufficient to save coral reefs. Ultimately, the solution to ensure the survival of coral reefs also depends on the success of an array of management systems in place across the world. The 50



Trends in Ecology & Evolution

Figure 2. Pyramid of Conservation Action for Ensuring the Long-term Future of Coral Reefs. (A) Conservation action will be futile if the underlying threat of climate change is not strongly mitigated under the Paris Climate Agreement of December 2015. Assuming success, however, coral reefs will still decline by between 70% and 90% on current levels of abundance. (B) Focusing on those coral reefs that are least vulnerable to climate change yet connected enough to provide good sources of future regeneration (Figure 1), however, suggests a long-term global strategy in which sites are identified, long-term investments made, and conservation strategies developed alongside community action to reduce and manage local-scale threats. Having a diverse portfolio of large sites as developed by Beyer *et al.* [20] will ensure that conservation does not simply ‘put all of its eggs into the one basket’.

large coral reef regions identified [20] (Figure 1) provide a diverse portfolio of reefs that hedges against future climate stress and that urgently requires investment in conservation interventions. Increased global support is needed to facilitate participatory multi-stakeholder reassessment of the conservation needs, socio-economic issues, and biodiversity values across the proposed portfolio (Box 2 and Figure 2). Of critical importance will be the reassessment of localized threats such as declining water quality, over-exploitation, habitat loss, invasive species, as well as the local exposure to increasing climate threats such as heat stress and intense storms.

Sustainable conservation requires that the full set of interactions between people, ecosystems, and economic systems be taken into account [22]. Strategies within each BCU might take on a variety of forms, depending on local circumstances (Figure 2). Actions might include reducing coastal pollution by encouraging sustainable farming practices [24,25], rebuilding fisheries through regulating access and implementing harvest controls [26], establishing protected areas [27], and/or diversifying reef economies with supplemental livelihoods (e.g., ecotourism, **low-impact aquaculture**, etc.) [28]. Long-term conservation solutions require the integration of the interests of governments, local communities, businesses and non-governmental organisations, and other stakeholders to strengthen the protection of these valuable areas, especially under the remaining climate stress before climate stabilization in achieved.

Transformative conservation among BCUs requires a coordinated scientific, policy, and local stakeholder response that reflects both short-term and long-term conservation and management goals (Figure 2). Each BCU will require varying amounts of increased financial, technical, and human resources according to the specific threats and local institutional capacity gaps. Though often highly localized, many threats to coral reefs are unfortunately ubiquitous: coastal and upland deforestation, untreated sewage and other point and non-point source pollution (i.e., agriculture), overharvesting, destructive fishing, and poorly planned coastal development [29]. While individual reefs need customized and locally appropriate conservation plans and management, the commonality of threats suggests continued opportunities for sharing experiences and technologies between BCUs and other regions that face similar challenges. The ongoing conservation of reefs also requires an adaptive approach to policy development and management that explicitly sets out to identify and resolve knowledge gaps in our understanding of coral reefs, the mechanisms by which stressors such as climate change impact corals, and linkages between social and ecological systems that drive these stressors.

While the central focus of Beyer *et al.* (2018) was to identify 50 coral reef regions (BCUs) with low vulnerability to climate change and high regeneration potential, the BCUs identified here also represent potential opportunities for developing and trialling novel adaptation technologies (e.g., **assisted evolution** [30]). These technologies may take years or decades to develop, hence the reduced ocean warming and storm risk may make these BCUs important as sources of robust coral stocks. The development of emerging technologies and methodologies [31] may provide important new opportunities for conservation. But many of these new technologies also come with significant risks, and hence it is essential that our scientific understanding of reef ecosystems be sufficient so that we avoid adverse outcomes that exacerbate rather than improve coral reef conservation outcomes. Substantial, long-term investment in research, as well as conservation and policy development, will be required to meet these questions and significant challenges.

The ultimate goal of the prioritization and strategy proposed here is to ensure that coral reefs continue to provide livelihoods, food security, and other key services for future generations, despite the expectation that these benefits may be greatly diminished in many places over the next few decades. In a rapidly changing climate, conservation planning requires a long-term perspective that accounts for projected changes in environmental conditions, which is a perspective that has sometimes been absent from previous planning exercises. In this regard, the strategy and portfolio of 50 reefs described here are intended to bolster and support, rather than compete with, the many excellent conservation efforts that are focused on coral reefs. This type of effort should be seen as a subset of efforts that may have slightly different short-term goals (e.g., preserving the greatest biodiversity or maintaining sustainable fisheries and food security) or scales (iconic reefs less than 500 km^2) but are likely to be complimentary in the longer term as the benefits and opportunity of networking and scale become apparent.

Paving the Way for Coral Reef Conservation

Prioritizing sites alone does not constitute a global strategy or policy in itself. However, it can increase global awareness, political commitment and inform strategic and innovative investment into the conservation of the world's coral reefs. In order to scale up interventions across the portfolio of selected BCUs, a shift in the global response to the current decline of coral reefs is needed. A recent report by UN Environment demonstrates that even with recent increases, not nearly enough is spent from sources such as overseas aid to ensure the preservation of the world's coral reefs [16]. The International Coral Reef Initiative has declared 2018 to be the third **International Year of the Reef (IYOR)**, but membership and financing for this initiative requires a significant boost to achieve its agenda. The recent declaration of UN **Sustainable Development Goal** 14 ('Life Below Water'), and its specific reference to threatened marine ecosystems is encouraging in terms of concern and action on coral reefs. Similarly, the 'Coral Reef Life Declaration' released at the October 2017 'Our Ocean' conference in Malta provides political momentum for increased coral reef action. These calls for action can now leverage strategic conservation plans across the world. The portfolio approach [20] is likely to also help elevate the profile of the problems and solutions for coral reef conservation at global scales. International funding partnerships, including the **Green Climate Fund**, **Global Environment Facility**, and major Bilateral Aid agencies might consider re-evaluating the level of support they provide to coral reef conservation. Substantial increases in our combined and coordinated efforts are required to ensure that the world's coral reefs will persist far into and beyond the **Anthropocene** [32].

Time is of essence when it comes to coral reefs. The third IYOR has been proclaimed, and is well underway in a year that started with devastating and unprecedented back-to-back mass coral bleaching and mortality across many countries [3]. More than ever, there is a need for global action and solutions that are effective and scalable, if we are to avoid the catastrophic loss and global decline of coral ecosystems. The solutions, however, are largely contingent upon the international community being able to deliver the goals of the Paris Climate Agreement. Emission reduction pledges [or **nationally determined contributions (NDCs)**] are central to the success or failure of the agreement, yet are currently inadequate and will, in their current form, drive global temperatures beyond 3°C above the preindustrial period if implemented [7]. Most analyses indicate that these conditions will remove coral reefs for a very long time, affecting hundreds of millions of people, and hence arguing for urgent action to secure greater greenhouse gas emission reductions through the Paris Climate Agreement and other national and subnational actions. Without effective action on climate change the future is clear: our earth will no longer be graced with one of the world's most spectacular and important ecosystems. With urgent action, however, we have the opportunity to preserve coral reefs in a state where there is good chance that they will regenerate once again in a more stable ocean and climate.

Acknowledgments

O.H.G., E.K., and H.B. are grateful for support from the Bloomberg Philanthropies, the Paul G. Allen Family Foundation, and the Tiffany and co. Foundation. O.H.G. was supported by an ARC Laureate Fellowship during this study, and was a member of the ARC Centre for Excellence in Coral Reef Studies through the University of Queensland. H.P.P. was supported by an ARC Laureate Fellowship during this study, and was a member of the ARC Centre for Excellence for Environmental Decisions through the University of Queensland.

Outstanding Questions

How do we integrate human and ecosystem concerns within sustainable business models aimed at preserving coral reefs while also improving opportunities for the communities who depend on them?

Are there innovations in finance (e.g., blue carbon, green bonds, ecosystem insurance) that can be harnessed for creating feasible, affordable, and sustainable solutions to the degradation of coral reefs,?

Are there opportunities for developing technologies that improve reef resilience, or speeding up reef recovery, once sites that are less vulnerable to climate change have been identified?

CellPress REVIEWS

References

1. Cinner, J.E. *et al.* (2012) Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. *Glob. Environ. Change* 22, 12–20
2. Pendleton, L. *et al.* (2016) Coral reefs and people in a high-CO_2 world: Where can science make a difference to people? *PLoS One* 11, 1–21
3. Hughes, T.P. *et al.* (2017) Global warming and recurrent mass bleaching of corals. *Nature* 543, 373–377
4. Hoegh-Guldberg, O. *et al.* (2014) The ocean. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Press, C.U., ed.), pp. 1655–1731, Cambridge University Press
5. Hoegh-Guldberg, O. (1999) Climate change, coral bleaching and the future of the world's coral reefs. *Mar. Freshw. Res.* 50, 839
6. UNFCCC Conference of the Parties (COP) (2015) *Paris Climate Change Conference-November 2015, COP 21*, 21932
7. Rogelj, J. *et al.* (2016) Paris agreement climate proposals need a boost to keep warming well below 2°C. *Nature* 534, 631–639
8. Frieler, K. *et al.* (2013) Limiting global warming to 2°C is unlikely to save most coral reefs. *Nat. Clim. Change* 3, 165–170
9. Donner, S. *et al.* (2005) Global assessment of coral bleaching and required rates of adaptation under climate change. *Glob. Change Biol.* 11, 2251–2265
10. Donner, S.D. (2009) Coping with commitment: projected thermal stress on coral reefs under different future scenarios. *PLoS One* 4, e5712
11. Darling, E.S. and Côté, I.M. (2018) Seeking resilience in marine ecosystems. *Science* 359, 986–987
12. Haisfield, K.M. *et al.* (2010) An ounce of prevention: cost-effectiveness of coral reef rehabilitation relative to enforcement. *Conserv. Lett.* 3, 243–250
13. Bayraktarov, E. *et al.* (2016) The cost and feasibility of marine coastal restoration. *Ecol. Appl.* 26, 1055–1074
14. Hughes, T.P. *et al.* (2010) Rising to the challenge of sustaining coral reef resilience. *Trends Ecol. Evol.* 25, 633–642
15. Anthony, K. *et al.* (2017) New interventions are needed to save coral reefs. *Nat. Ecol. Evol.* 1, 1420–1422
16. UN Environment (2018) *Analysis of International Funding for the Sustainable Management of Coral Reefs and Associated Coastal Ecosystems. Coral Reef Initiative, UN Environment World Conservation Monitoring Centre.* wcmc.io/coralbrochure
17. Page, G.G. (2015) *A Synthesis of Issues Affecting the Management of Coral Reefs and Recommendations for Long-Term Capacity Building in U.S. Jurisdictions,* National Oceanic and Atmospheric Administration's Coral Reef Conservation Program
18. Iwamura, T. *et al.* (2010) A climatic stability approach to prioritizing global conservation investments. *PLoS One* 5
19. Klein, C.J. *et al.* (2010) Prioritizing land and sea conservation investments to protect coral reefs. *PLoS One* 5, e15103
20. Beyer, H.L. *et al.* (2018) Risk-sensitive planning for coral reef conservation under rapid climate change. *Conserv. Lett.* Published online June 27, 2018. http://dx.doi.org/10.1111/conl.12587
21. Markowitz, H.M. (1952) Portfolio selection. *J. Finance* 7, 77–91
22. Ando, A.W. and Mallory, M.L. (2012) Optimal portfolio design to reduce climate-related conservation uncertainty in the prairie pot-hole region. *Proc. Natl. Acad. Sci. U. S. A.* 109, 6484–6489
23. Runting, R.K. *et al.* (2018) Reducing risk in reserve selection using modern portfolio theory: coastal planning under sea-level rise. *J. Appl. Ecol.* 55, 2193–2203
24. Jupiter, S.D. *et al.* (2017) Opportunities and constraints for implementing integrated land-sea management on islands. *Environ. Conserv.* 44, 254–266
25. Kroon, F.J. *et al.* (2016) Towards protecting the Great Barrier Reef from land-based pollution. *Glob. Change Biol.* 22, 1985–2002
26. McClanahan, T. *et al.* (2016) Establishment of community managed fisheries' closures in Kenya: early evolution of the tengefu movement. *Coast. Manage.* 44, 1–20
27. Mellin, C. *et al.* (2016) Marine protected areas increase resilience among coral reef communities. *Ecol. Lett.* 19, 629–637
28. Cinner, J.E. *et al.* (2013) Evaluating social and ecological vulnerability of coral reef fisheries to climate change. *PLoS One* 8, e74321
29. Wear, S.L. (2016) Missing the boat: critical threats to coral reefs are neglected at global scale. *Mar. Policy* 74, 153–157
30. van Oppen, M.J.H. *et al.* (2015) Building coral reef resilience through assisted evolution. *Proc. Natl. Acad. Sci. U. S. A.* 112, 2307–2313
31. Rau, G.H. *et al.* (2012) The need for new ocean conservation strategies in a high-carbon dioxide world. *Nat. Clim. Change* 2, 720–724
32. Hoegh-Guldberg, O. (2014) Coral reefs in the Anthropocene: persistence or the end of the line? *Geol. Soc. Spec. Publ.* 395, 167–183
33. Bunce, L. and Pomeroy, B. (2003) *Socioeconomic Monitoring Guidelines for Coastal Managers in Southeast Asia: SocMon SEA,* Global Coral Reef Monitoring Network
34. Pomeroy, R.S. *et al.* (2005) How is your MPA doing? A methodology for evaluating the management effectiveness of marine protected areas. *Ocean Coast. Manage.* 48, 485–502
35. Stolton, S. *et al.* (2003) *Reporting Progress at Protected Area Sites,* World Bank/WWF Alliance for Forest Conservation and Sustainable Use
36. Roelfsema, C. *et al.* (2018) Coral reef habitat mapping: a combination of object-based image analysis and ecological modelling. *Remote Sens. Environ.* 208, 27–41