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LETTER

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Risk-sensitive planning for conserving coral reefs under rapid climate change

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Abstract

Coral reef ecosystems are seriously threatened by changing conditions in the ocean. Although many factors are implicated, climate change has emerged as a dominant and rapidly growing threat. Developing a long-term strategic plan for the conservation of coral reefs is urgently needed yet is complicated by significant uncertainty associated with climate change impacts on coral reef ecosystems. We use Modern Portfolio Theory to identify coral reef locations globally that, in the absence of other impacts, are likely to have a heightened chance of surviving projected climate changes relative to other reefs. Long-term planning that is robust to uncertainty in future conditions provides an objective and transparent framework for guiding conservation action and strategic investment. These locations constitute important opportunities for novel conservation investments to secure less vulnerable yet well-connected coral reefs that may, in turn, help to repopulate degraded areas in the event that the climate has stabilized.

KEYWORDS
climate change, connectivity, conservation, coral reef, cyclone, global, ocean warming, optimization, planning, portfolio theory

1 | INTRODUCTION

Anthropogenic climate change is driving major changes to ecological, agricultural, and social systems on both land and sea, although these effects are highly variable in space and time (Hoegh-Guldberg et al., 2014; IPCC, 2013; Le Quere et al., 2016). There is robust evidence of the large-scale transition of marine ecosystems to simpler, less diverse, or even highly degraded states (Garcia Molinos et al., 2015; Gattuso *et al.*, 2015; Hughes et al., 2017a). Consequently, decisive action on climate change is urgently needed, especially for the hundreds of millions of people who are dependent on vulnerable coastal resources (Cinner, 2014; Costanza et al., 2014). However, the continuously changing and uncertain conditions associated with climate change present unique challenges for conservation. By failing to account for changing conditions, for example, limited conservation resources may be targeted at places that are at high risk of severe climate-related degradation leading to conservation failure or poor return on investment. Coordinating conservation efforts at a global scale, therefore, provides important opportunities for strategic planning that can reduce the risk of widespread failure.

Here, we describe a strategy to identify and protect coral reefs in the context of rapid climate change. Coral reef ecosystems are threatened by local (e.g. declining water quality, overfishing [Riegl, Bruckner, Coles, Renaud, & Dodge, 2009]) and global stressors (e.g. ocean warming [Heron, Maynard, van Hooidonk, & Eakin, 2016], storms [De'ath, Fabricius, Sweatman, & Puotinen, 2012]) and are likely to disappear by mid-to-late century if the emission reduction goals of the Paris Agreement are not met (Hoegh-Guldberg et al., 2014; UNFCCC, 2015, Figure 1). Even if they are met, an estimated 70–90% of the world's corals could disappear by mid-century (Donner, Skirving, Little, Oppenheimer, & Hoegh-Guldberg, 2005; Frieler et al., 2013; van Hooidonk et al., 2016). The remaining coral populations, however, are arguably important for the replenishment of coral reefs once ocean surface temperatures have stabilized in the future (Figure 1c; Hoegh-Guldberg et al., 2014). Corals that persist into the relatively more stable conditions of a successful Paris Agreement outcome would likely act as important sources of larvae, as long as they are connected to reefs that require replenishment and have minimized the risks of other stressors such as storms (Hoegh-Guldberg, 2014). Once identified, the global strategy might be to protect these important areas from local nonclimate change threats (e.g. pollution, overexploitation). The key challenge is to systematically and robustly identify these reefs to direct new management resources focused on achieving long-term coral conservation outcomes in the context of climate change.

The problem of maximizing investment returns while minimizing the risk of losses is well understood by financial investors. Modern portfolio theory (MPT) is a formal mathematical framework for identifying a set of investments that maximizes returns while reducing the variance in those returns according to the degree of risk-aversion of the investor (Markowitz, 1952). It is founded on the idea that while the future return on investments is uncertain, there are a wide

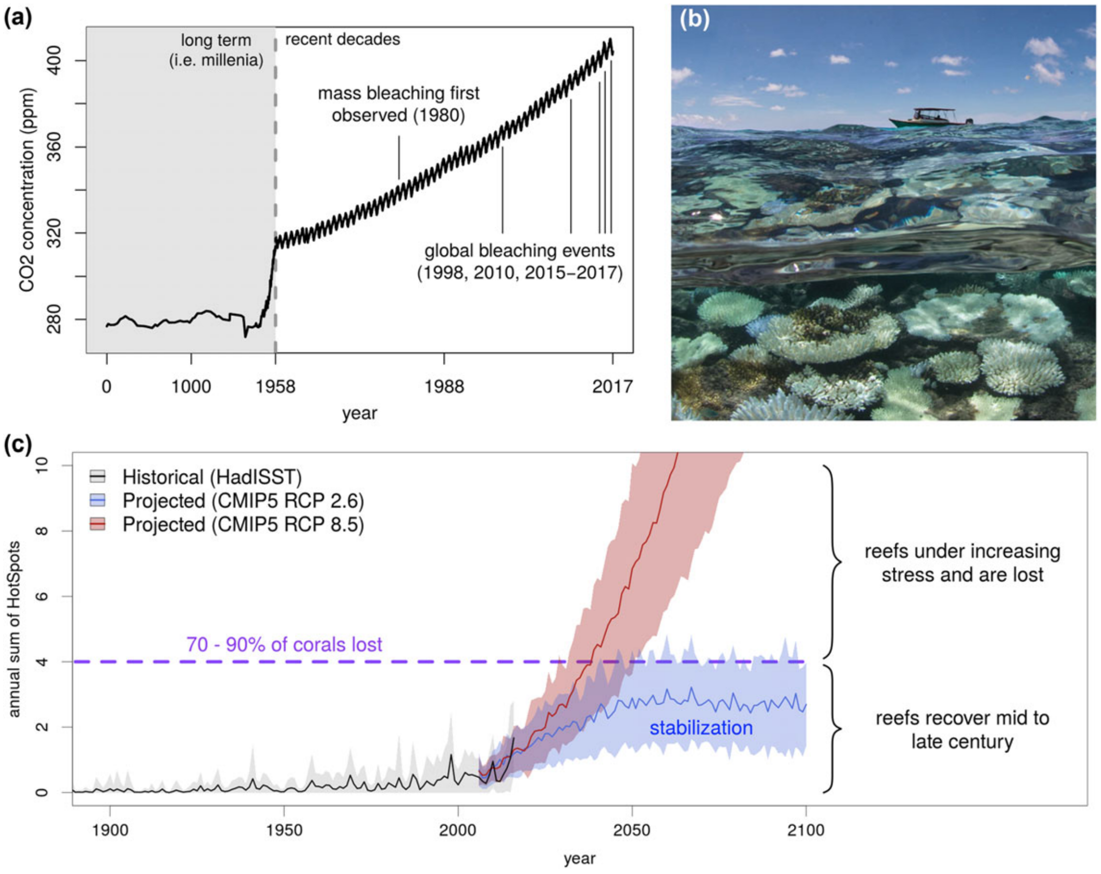

FIGURE 1 (a) Trend in the atmospheric concentration of carbon dioxide (CO_2) over the previous two millennia (31, 32) in relation to the timing of mass coral bleaching events. (b) An example of coral bleaching from the Maldives. Coral mortality often increases dramatically following extensive mass coral bleaching (R. Vevers 2015, with permission). (c) Historical (Hadley Centre Sea Ice and Sea Surface Temperature dataset; black line) and future projected annual sum of anomalies ("HotSpots") for coral-containing regions (19 climate models, CMIP5, IPCC 2013) under the most and least optimistic climate projections (RCP 2.6, blue, and RCP 8.5, red, respectively)

range of positive and negative correlations among investment values through time that provide opportunities to reduce the variance in overall returns. By selecting a portfolio of negatively correlated or uncorrelated investments, if some of the investments perform poorly others may still perform well. Thus, MPT is an approach to developing a diversified portfolio that maximizes returns for a given chance of catastrophic losses arising from poor performance of all investments.

The corollary in conservation planning is that future conservation benefits (returns) arising from investment are also uncertain. By applying MPT to conservation planning, the expected variance in those conservation outcomes can be reduced by investing in areas that tend to behave in different ways (Ando & Mallory, 2012; Runting et al., 2018). This is of particular interest when decisions about where to act are informed by uncertain projections about future states of the world, as is often the case with climate change projections. Notably, while both the spatial distribution of climate change impacts and financial risk may be hard to predict, ignoring the best available predictions is certainly worse than embracing them.

We conducted a global scale analysis to identify a portfolio of regions in which long-term coral reef conservation investment might be least subject to impacts from climate change (e.g. thermal stress and coral bleaching), while including reefs with a capacity to repopulate other reefs over time, and that are not likely to be frequently devastated by cyclones. Planning at a global scale provides an opportunity to reduce risk in the portfolio by selecting complementary sites that reduce the expected variance in benefits–an opportunity that may be diminished when planning at finer scales. Together with information on more local conditions and threats, this information can inform strategic conservation investments.

2 | METHODS

A key difficulty in applying quantitative approaches to spatial planning is identifying ecologically relevant measures of climate change threats and their relative importance (Pacifici et al., 2015). To reduce reliance on a small number of measures, we explored an extensive array of climate- and connectivity-related variables that we postulate are important to the viability of coral reefs and focused in on 30 metrics relevant to coral reef ecology across five major themes (Table 1): historical (1985–2017) thermal conditions (13 metrics), predicted future thermal conditions (8 metrics estimated for each of 19 global climate model projections), larval connectivity and settlement (Wood, Paris, Ridgwell, & Hendy, 2014, 2 metrics), cyclone wave damage (Carrigan & Puotinen, 2011, 3 metrics) and recent thermal conditions (particularly from the damaging 2014–2017 global coral bleaching event [Hughes et al., 2017b]; 4 metrics). Although many other environmental and social factors are known to impact reefs (Supporting Information Table S1), these five themes were selected because there is little potential to manage them directly, so avoiding these threats and favoring connected areas is prudent, and many of the other themes are not comprehensively mapped at global scales. Historical climate data were considered alongside climate projections because they have better resolution and accuracy, and may serve as a measure of the spatial distribution of future impacts.

An aggregate score for the suitability of coral reefs (Figure 2a; henceforth "suitability metric") was derived by evaluating every unique combination of a single, standardized metric (mean 0 and unit variance standardization, with the sign changed such that higher values are more desirable) selected from each data theme, evaluated across each of 38 relative weightings among data themes (SM S1). The alternative weights among data themes (Supporting Information Figure S1) reflect a wide range of perspectives on the relative importance of each data theme for informing coral reef conservation planning. The weights were based on feedback from a scientific panel consisting of experts in coral ecology, taxonomy, and physiology, climate change impacts on corals, oceanography, and conservation planning (SM, Supporting Information Table S2). Thermal history and thermal future metrics had the highest weights as they were deemed to be the most significant threat measures for informing long-term planning. The cyclone and connectivity measures received the next highest set of weights, reflecting the desire to avoid cyclone impacts and favor areas that have greater potential to repopulate other areas. Recent thermal conditions received the lowest weights and were included so that, all other things being equal, we would rather select sites that have not suffered recent thermal stress and degradation where possible. The purpose of evaluating a varied set of such weights is to reduce the sensitivity of the analysis to the choice of any one vector of weights, which may be arbitrary. The suitability metric for each reef was generated by averaging the 1.8 million combinations of standardized metrics and relative weights (Figure 2a).

Our goal was to identify a set of bioclimatic units (BCUs) that contain approximately 500 km^2 of reefs. This size of BCU is likely to capture a range of marine habitat types, genetic diversity, and ecological processes (McLeod, Salm, Green, & Almany, 2009), while providing opportunities for applying a variety of conservation measures across a range of scales. This scale affords a reasonable chance that some reefs within each BCU will persist even if many of the reefs are impacted by climate change. The suitability metric was calculated at an approximately 25 km^2 cell resolution. We used a custom, iterative clustering algorithm to identify 162 BCUs (SM Figure 3) from these cells, representing the top 50% of the distribution of suitability metrics of reefs globally. This algorithm maximized the quality of each BCU while also penalizing the inclusion of cells in proportion to their distance from current members of the cluster (SM S1).

Covariance among BCUs was quantified using the scores, averaged among constituent reefs within the BCU. Risk-return trade-offs were quantified across a range of selection sizes (5–80) using MPT implemented in an integer quadratic programming framework (Runting et al., 2018). To encourage a broad coverage of global biodiversity/biogeography, the problem was constrained to permit a maximum of three BCUs to be selected in each ecoregion (Spalding et al., 2007) (see SM S1 for further details on methods). All spatial analysis was implemented in R version 3.3.2 (R Core Team, 2016) using the "raster" and "sp" packages, and the quadratic programming problems were solved using Gurobi version 7.5.2 (Gurobi Optimization, Inc., 2016).

3 | RESULTS

Regions that are projected to experience relatively lower levels of threat impact, as measured by the suitability metric, include portions of central and western portions of southeast Asia (the Philippines, Borneo, Indonesia), Australia's Great Barrier Reef, French Polynesia, East Africa, the Red Sea, and the Caribbean (Figure 2a). These patterns are in broad agreement with previous global analyses of climate impacts on coral (Heron et al., 2016; Maina, McClanahan, Venus, Ateweberhan, & Madin, 2011; Pendleton et al., 2016; Wolff et al., 2015). Several regions containing reefs of high ecological and social value that are projected to suffer higher levels of impacts include, for example, Hawaii, Meso-American Reef, and Western Australia. Local variation in projected impacts within these areas may provide important opportunities for conservation at finer spatial scales than those targeted in this project.

Our study identified a global portfolio of 50 BCUs for conservation investment that maximizes the chance these reefs are secure in the future (Figure 4; Table 1). This portfolio solution represents a substantial opportunity to reduce the variance of expected conservation returns at a global scale with a relatively small reduction in the total value of the net benefit across a wide range of solution sizes (Figure 3a and b). In other words, by investing significantly in the survival of coral reefs across this portfolio of reefs, the likelihood of

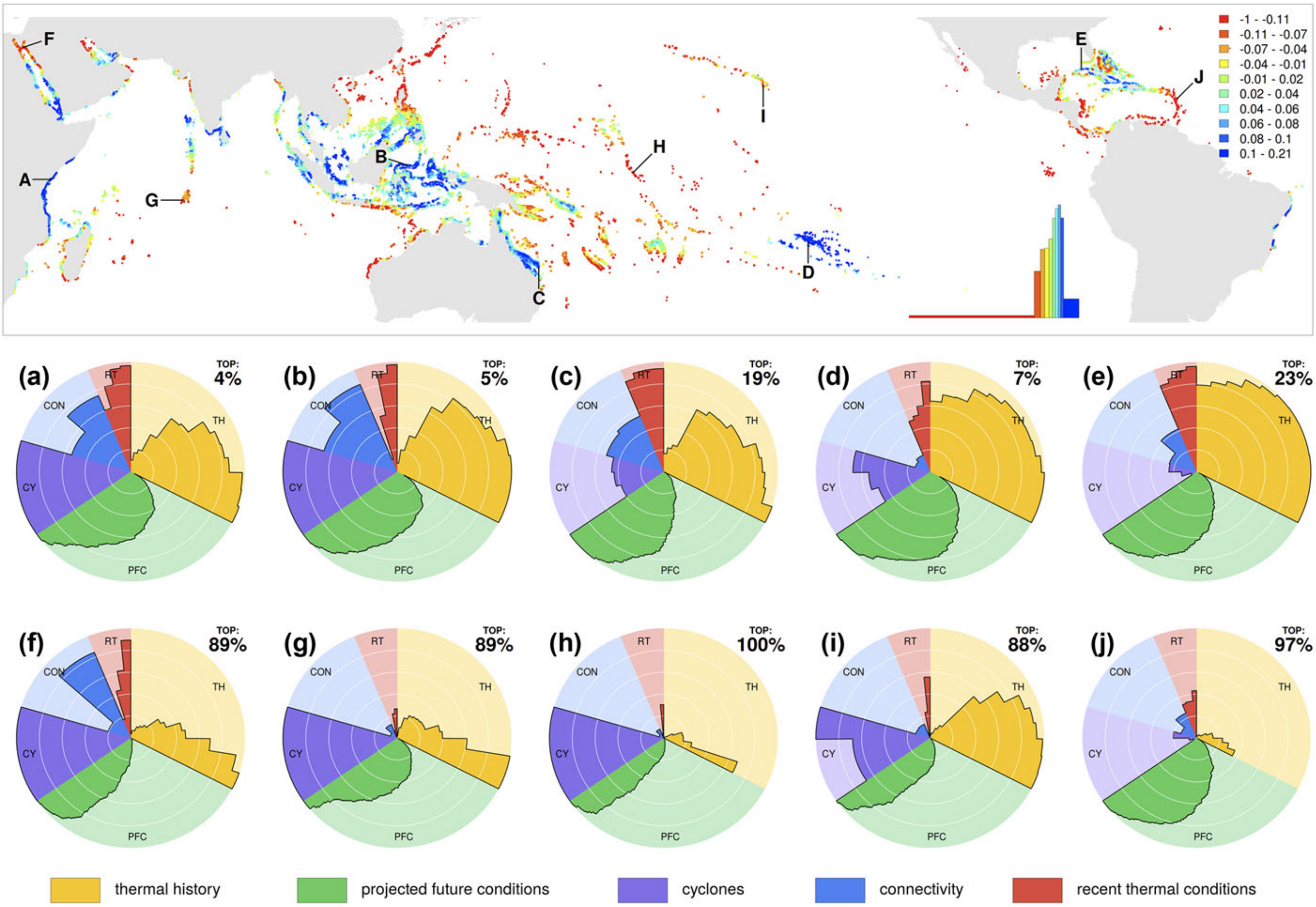

FIGURE 2 Relative scores of performance for Bioclimatic Units (BCUs) with respect to 30 metrics (top panel). Labels indicate the location of examples of sites that perform relatively well (a–e) and poorly (f–j) with respect to historical thermal stress (TH; orange), projected future conditions for each of 19 climate models (PFC; green), cyclones (CY; purple), connectivity among reefs (CON; blue), and recent thermal conditions in the previous two warm seasons (RT; red). Each radial segment represents a single metric, expressed as the percentile of that value relative to all other coral reef locations (the 20, 40, 60, and 80 percentiles are represented in each radial plot by concentric white circles for reference). In essence, the larger the petals, the better the site. Within each data theme metrics are displayed in ascending order to improve interpretation. The number in the upper right of each plot represents the overall percentile of the site relative to all other coral reefs

conservation success is improved. For example, the portfolio of 50 BCUs presented here represents a solution in which a 54.4% reduction in the variance of returns can be achieved with only a 5.9% reduction in total return relative to the “maximum return” solution (Figure 3b). This balanced solution includes reefs in 31 of the 87 countries that have more than 500 km^2 of tropical coral reefs, with multiple BCUs in countries such as Australia, Cuba, French Polynesia, Philippines, Bahamas, and Malaysia (Figure 4). This solution also includes 36 of 150 Corals of the World ecoregions, between them containing 95% of the documented species of corals (Veron, Stafford-Smith, Turak, & DeVantier, 2017) and representatives in 31 of the 232 Marine Ecoregions of the World (an alternative ecoregion map) (Spalding et al., 2007), which contain approximately 68% of all coral reefs.

We then compared the performance of coral reefs within the portfolio of BCUs with the remaining, unselected coral reefs. Although there was considerable variation among metrics (Table 1), overall, selected reefs performed 42%, 11%, 56%, 15%, and 18% better than unselected BCUs with respect to thermal history, projected future conditions, cyclone exposure, connectivity, and recent thermal metrics, respectively. Relative to unselected coral reefs BCU cells, the selected coral reef BCU cells historically experienced, for example, a 2.7°C-week (35.1%) lower maximum degree heating week (DHW), 15.6 and 3.6 days (20.1% and 65.3%) less annual exposure to DHW greater than 0°C and 4°C, respectively, and a 0.41°C-day (28.9%) lower trend of increasing annual exposure to temperature anomalies (“HotSpots”). In the future, they were projected to experience 0.62 months decade^{-1} (12.2%) fewer hotspots greater than 1°C and 0.14°C-months (4.2%) lower maximum degree heating months. They also experienced, on average, 1.3 days less exposure to cyclones per year, 4.7 days lower maximum days of exposure to cyclones over

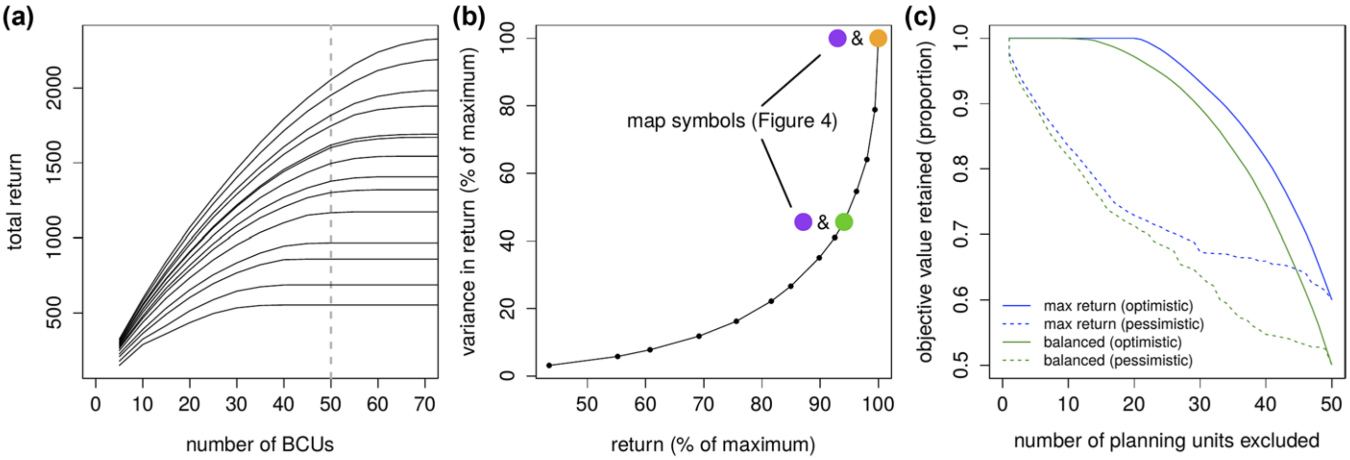

FIGURE 3 The spatial planning optimization problem was solved over a wide range of levels of risk-aversion and numbers of planning units selected. Across all of these scenarios, objective function values typically approached an asymptote with between 30 and 70 planning units (a) Lines represent levels of risk-aversion ranging from none (upper line) to strong risk-aversion (bottom line). For the 50 planning unit solution, the risk-return trade-off (b) indicates that substantial reductions in the variance of returns can be achieved with a relatively small reduction in returns. The difference between the maximum return solution (purple and orange dots) and a balanced solution (purple and green dots) is shown in Figure 4. There was some potential to achieve similar performance with different sets of planning units in the balanced solution (c), depending on which sets of planning units were lost

an extended time period, and were free from exposure to cyclones (return interval) 5 years longer. Variation in performance among individual metrics arises from complex patterns in the codistribution of values that determine the degree to which selected reefs can address multiple criteria simultaneously. The low performance with respect to thermal future metrics arises from both the disagreement in the spatial distribution of warming among the climate models, and the considerably coarser spatial scale at which those projections are made compared to the other datasets, which reduces opportunities to avoid those impacts. Performance of the portfolio with respect to future climate conditions is expected to increase as the resolution of climate models improves, which should also enable more robust simulations of future cyclones.

Although this approach identifies one specific portfolio, other combinations of BCUs may perform similarly well. Our analysis indicates, however, that performance of the balanced solution can decline markedly as these BCUs are excluded (Figure 3c), depending on which combinations of BCUs are excluded. If some BCUs are impractical to manage for reasons such as impacts of intensive coastal development, or challenges of politics, security, etc., this framework would be capable of identifying the best alternative portfolio after the removal of these BCUs.

4 | DISCUSSION

Our analysis provides a robust approach to identify portfolios of coral reef conservation options under climate impacts that explicitly reduces risk arising from uncertainties in future conditions. Of particular interest are places where there is currently little conservation attention, but where climate impacts may be relatively low–such as northern Sumatra and the southern Red Sea. In reality, some of these areas may already be highly degraded, but could still represent important conservation opportunities, due to their projected long-term prospects of more suitable environmental conditions. Reefs in BCUs that are degraded due to tractable local threats (e.g. solving water quality problems or managing exploitation) may also represent key opportunities for effective conservation intervention, as the transition from a degraded to a "healthy" and biodiverse reef can restore many now-absent ecological, economic, and social benefits.

Ignoring uncertainty associated with future conditions would be a high-risk planning strategy (Runting et al., 2018). Two important risks are investing limited resources in locations where reefs are not able to persist over the coming decades, thereby sacrificing the opportunity to achieve meaningful conservation in other areas, and the risk of investing in a portfolio of locations that ultimately may all be more susceptible to climate change than predicted (the risk of widespread failure across the portfolio). By employing a diversity of metrics to quantify threats, and using MPT to generate a balanced portfolio, our approach attempts to reduce these risks. Moving forwards, expansion of MPT approaches could build in other datasets related to cover reef condition, ocean acidification, the threats from more local scale variables such as invasive species and eutrophication from run-off, socio-economic context, or indeed other global change variables, thereby developing alternative portfolios. Improvements in the spatial resolution of datasets would also facilitate identification fine-scale

TABLE 1 Performance of reefs in the selected portfolio relative to unselected reefs, with respect to 30 climate and connectivity metrics

Thermal history (1985–2017)	**Mean (S)**	**Difference**	**Improvement (%)**
Annual sum HotSpots > 0°C (°C-days)	32.0	−5.7	15.0
Annual sum HotSpots > 1°C (°C-days)	5.2	−4.5	46.5
Annual sum HotSpots > 2°C (°C-days)	0.1	−0.3	84.6
Maximum HotSpots, entire record (°C)	1.9	−0.2	11.3
Annual number of days with HotSpots > 0°C (days)	79.9	0.0	0.0
Annual number of days with HotSpots > 1°C (days)	4.3	−3.4	44.1
Annual number of days with HotSpots > 2°C (days)	0.0	−0.1	83.9
Maximum DHW (°C-weeks)	5.0	−2.7	35.1
Annual number of days with DHW > 0 (days)	62.1	−15.6	20.1
Annual number of days with DHW > 4 (days)	2.3	−4.4	65.3
Annual number of days with DHW > 8 (days)	0.1	−1.0	90.7
Trend in annual sum of HotSpots > 0°C (°C-days yr^{-1})	1.0	−0.4	28.9
Trend in summer SST (°C decade^{-1})	1.49×10^{-2}	-4.14×10^{-3}	21.8
			42.1
Projected future conditions (2006-2050)			
Maximum monthly HotSpots, entire record (°C)	0.3	0.0	4.5
Maximum DHM, entire record (°C-months)	0.7	0.0	4.2
Decadal number of months with HotSpots > 1°C (months)	4.5	−0.6	12.2
Decadal number of months with HotSpots > 2°C (months)	0.1	−0.1	44.2
Decadal sum of monthly HotSpots > 1°C (°C- months)	3.3	−0.6	16.0
Trend in annual maximum monthly HotSpot (°C decade^{-1})	1.01×10^{-2}	-3.37×10^{-4}	3.2
Trend in annual maximum DHM (°C-months decade^{-1})	2.56×10^{-2}	-7.06×10^{-4}	2.7
Trend in annual sum hotspots > 0°C (°C-months decade^{-1})	4.22×10^{-2}	1.09×10^{-3}	−2.6
			10.5
Cyclones			
Annual average days exposure (days)	0.6	−1.3	66.8
Annual maximum days exposure (days)	4.7	−4.7	50.0
Inverse return time interval (1 day exposure) (yr^{-1})	0.1	−0.1	51.4
			56.1
Connectivity			
Larval outgoing settlement (includes self-recruitment; proportion)	0.8	0.1	14.5
Larval export (no self-recruitment; proportion)	0.7	0.1	16.0
			15.2
Recent thermal history			
Sum hotspots > 0°C (degree days yr^{-1})	4.1	−1.0	18.8
Maximum hotspot (°C)	1.5	−0.2	12.1
Number days hotspot > 0°C (d yr^{-1})	8.0	−0.1	1.0
Maximum DHW (degree weeks)	3.7	−2.5	40.4
			18.1

Mean performance values for each theme are shown in bold.

refugia that may be important for conservation. There remain, however, considerable challenges to mapping such variables at global scales.

The portfolios we evaluated excluded several ecologically significant areas, such as Hawaii and the Meso-American Barrier Reef. Although there is often variation in projected impacts within these regions, implying opportunity for strategic conservation planning, the best-performing areas may not have occurred over as large an area as other locations globally. The presented MPT approaches could subsequently be applied to inform conservation planning at national or regional scales. Similarly, criteria relevant to coral reef

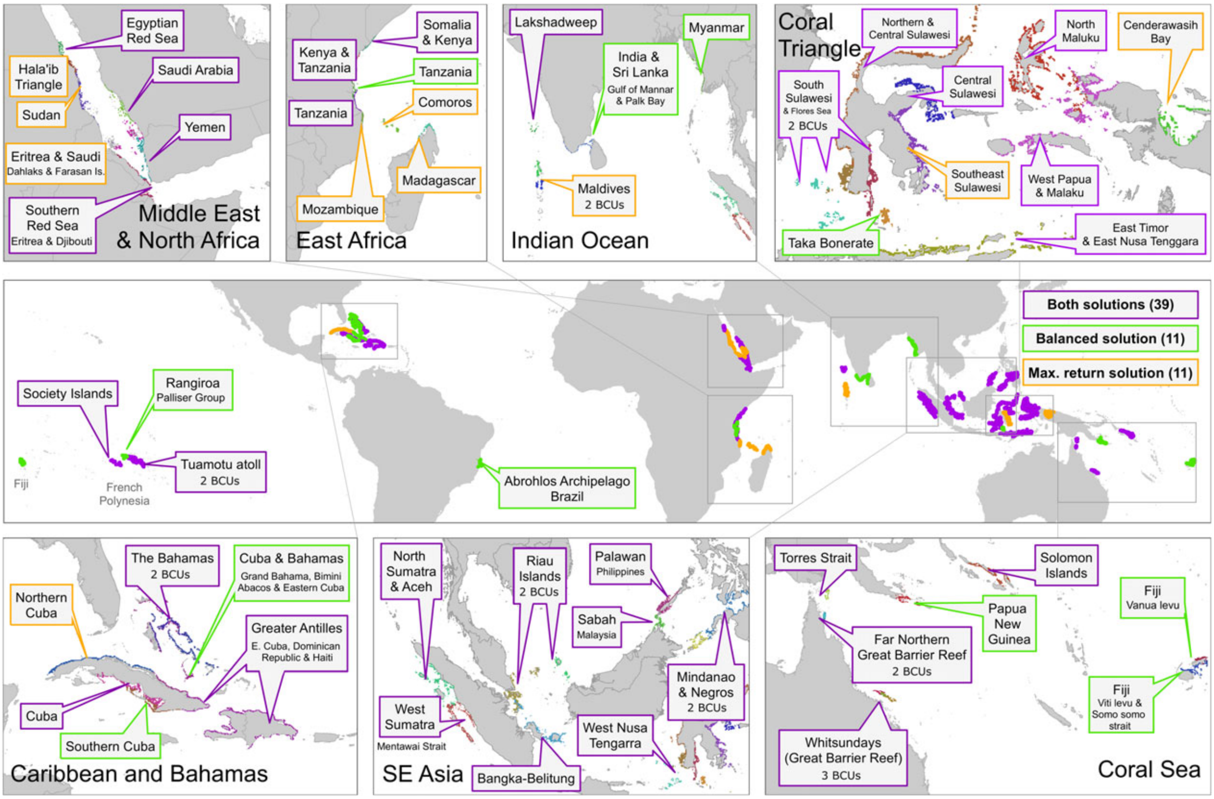

FIGURE 4 Map of the 50 bioclimatic units (BCUs) selected in the maximum return (purple and orange in middle panel) and balanced scenarios (purple and green in middle panel). The balanced scenario represents the optimal portfolio presented in this paper. Colors of BCUs in the other panels have no significance and serve only to distinguish individual BCUs

conservation that were not considered in this study because data were not available globally–such as ocean chemistry, ecological adaptive capacity of reefs (Anthony et al., 2015) or the human dependence on coral reef ecosystems (Pendleton et al., 2016)–could be incorporated into MPT analyses to inform conservation priorities at subglobal scales.

In all conservation interventions, reducing concomitant threats is the key to improving resilience (Anthony et al., 2015). While our work helps identify areas where reef survival may be greatest in the face of warming oceans and cyclones, current management interventions may still not be sufficient to keep these reefs healthy. More active interventions, such as assisted colonization or even assisted evolution, may require serious consideration if we are to secure a future for these important habitats (Anthony et al., 2017; Rau, McLeod, & Hoegh-Guldberg, 2012; van Oppen *et al.*, 2017). Research is urgently required to establish the scientific basis for these emerging technologies, to identify potential risks and adverse outcomes that could arise from deploying them, and protocols for improving their success.

There is little doubt that the future of coral reefs hangs in the balance. Investment in protecting any portfolio of reefs will be insufficient if carbon emissions are not reduced. The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement, which has been ratified by 172 of the 197 parties, aims to limit average global temperature increases to below 2°C (striving for 1.5°C in the longer term) relative to preindustrial levels. Although more ambitious emission reductions than those agreed to in Paris will be required to achieve these targets (Rogelj et al., 2016), the Paris Agreement represents our best hope of avoiding the most catastrophic impacts of climate change. Although widespread loss and degradation of coral reefs due to climate change is expected over the coming decades (Hoegh-Guldberg et al., 2014; Hughes et al., 2018), strategic management of local and global threats, along with emerging technologies, provide opportunities for us to improve the long-term conservation and persistence of coral reefs. Success in saving coral reefs, however, ultimately depends on the global community meeting or exceeding the science-based targets agreed to in Paris in December 2015.

CONFLICT OF INTEREST

The authors have declared no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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