

LETTER

The Effect of Applying Alternate IPCC Climate Scenarios to Marine Reserve Design for Range Changing Species

Azusa Makino¹, Carissa J. Klein¹, Hugh P. Possingham^{1,4}, Hiroya Yamano², Yumiko Yara², Toshinori Ariga³, Keisuke Matsuhashi³, & Maria Beger¹

¹ Australian Research Council Centre of Excellence for Environmental Decisions, School of Biological Sciences, The University of Queensland, Brisbane, QLD, 4072, Australia

² Center for Environmental Biology and Ecosystem Studies, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki, 305-8506, Japan

³ Center for Social and Environmental Systems Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki, 305-8506, Japan

⁴ Department of Life Sciences, Imperial College-London, Silwood Park, Ascot, SL5 7 PY, UK

Keywords

Climate change; climate model; coral; IPCC; marine conservation; marine protected area; Marxan; Representative Concentration Pathway; sea-surface temperature; spatial prioritization.

Correspondence:

Azusa Makino, Australian Research Council Centre of Excellence for Environmental Decisions, School of Biological Sciences, The University of Queensland, Brisbane, QLD 4072, Australia. Tel: +61733467541; fax: +61733651655. E-mail: azusamakino@gmail.com

Received

14 January 2014

Accepted

7 October 2014

Editor

Andrew T. Knight

doi: 10.1111/conl.12147

Abstract

Effectively protecting of biodiversity in the future relies on reserves that accommodate potential climate change impacts. Climate predictions are based on plausible ranges of greenhouse gas concentration scenarios from the IPCC, called Representative Concentration Pathways (RCPs). It is unknown how different scenarios influence spatial prioritization, particularly for species that change their range due to climate change. Using corals in Japan, we explore differences in priorities under three RCPs (RCP8.5, 4.5, and 2.6), comparing three time frames (current conditions, near future, and distant future). We targeted three temperature zones representing different coral community types, determined from predictions of sea-surface temperature for three RCPs. Results showed that using one RCP prediction to design a reserve system does a poor job at meeting conservation targets for other RCPs, missing up to 100% of the targets. We emphasize the importance of focusing conservation investment in “no regrets” areas that are important under every RCP.

Introduction

Spatial prioritization provides decision-support information to planners about where to protect areas to meet conservation targets (Pressey & Bottrill 2009). It is important to consider future climates in spatial prioritization to ensure that reserves are effective not only under current environmental conditions, but also under future environmental conditions (Araújo *et al.* 2004; Carvalho *et al.* 2011; Makino *et al.* 2014). An increasing number of studies address climate change, particularly increasing sea-surface temperatures (SST), in marine spatial prioritization (Game *et al.* 2008; McLeod *et al.* 2010; Levy &

Ban 2013; Makino *et al.* 2014). These studies use either a single future climate scenario for SST prediction (Game *et al.* 2008; McLeod *et al.* 2010; Makino *et al.* 2014), or use two scenarios (Levy & Ban 2013) but do not investigate how priority areas change if we use different future climate scenarios.

The greenhouse gas concentration trajectories “Representative Concentration Pathways (RCP)” were developed for the Intergovernmental Panel on Climate Change (IPCC) to provide a framework for modeling for its fifth Assessment Report (Moss *et al.* 2010). These RCPs span the range of radiative forcing (i.e., the change in the balance of receiving and emitting radiation in the

atmosphere system of the Earth) levels by 8.5, 6, 4.5, and 2.6 W/m², respectively, by 2100 (Moss *et al.* 2010). RCP8.5 is a substantially rising pathway, whereas RCP2.6 has a peak and decline trajectory (peak of 3 W/m² before 2100 followed by a decline). RCP4.5 and RCP6 are intermediate pathways. Current CO₂ emissions track at or above RCP8.5, but there is still a possibility to shift to other pathways (Peters *et al.* 2013). While we acknowledge that RCP2.6 seems unlikely, we used it to represent the portfolio of options currently considered by the IPCC and because a robust prioritization should account for even unlikely futures as decision-support information for policy makers. The range losses in common and widespread species, that are the impacts of different future scenarios on terrestrial biodiversity, have been shown in other studies (Warren *et al.* 2013). However, influences of different RCP scenarios on potential marine spatial conservation priorities remain untested. Considering the differences in scenarios in spatial prioritization is crucial especially for protecting species with shifting ranges.

Scleractinian corals are changing their ranges into higher latitudes in response to the increase of SST, as seen in Japan (Yamano *et al.* 2011), Australia (Baird *et al.* 2012), and the Caribbean (Precht & Aronson 2004). SST has increased over the last 100 years with considerable spatial heterogeneity (Deser *et al.* 2010). The resulting thermal regime, combined with changing light availability and aragonite ion concentrations (Kleypas *et al.* 1999), renders it unlikely that many coral species will persist in their current core ranges by the end of century (Donner 2009; Frieler *et al.* 2013; van Hooidonk *et al.* 2013). This is because thermal stress caused by elevated SST can trigger the breakdown of the symbiosis between corals and zooxanthellae, leaving corals vulnerable to coral bleaching (Donner 2009). Coral reefs are in decline worldwide due to anthropogenic and climate change related impacts (Burke *et al.* 2011; Pandolfi *et al.* 2011). Therefore, poleward range expansions may allow corals to escape thermal stress and persist in tropical regions at high latitudes (Beger *et al.* 2014). Previous studies (Game *et al.* 2008; Levy & Ban 2013; Mumby *et al.* 2011) made substantial progress toward incorporating impacts of climate change on coral reefs in spatial planning, but their focus was on SST and coral bleaching. Here, we focus on how planning under different RCP scenarios impacts the protection of coral reefs predicted to expand their distribution poleward.

We evaluate different attributes among marine reserves to protect habitat for range changing corals in Japan designed for three RCPs (RCP8.5, 4.5, 2.6) by exploring the following questions: (1) how do marine reserves differ in size, cost, and spatial configuration under

alternative future climates?; (2) can we identify “no regrets” priority areas that are consistently priorities for all three RCPs (i.e., RCP8.5, 4.5, 2.6)?; and (3) what RCP should we use when we plan using a single RCP?

Methods

Study region

Our study region is Japan, representing the latitudinal transition zone of coral communities from subtropical to temperate (Yamano *et al.* 2011). We considered the rocky areas within 1 km of the coastline and less than 100 m depth as current and potential sites for corals now and in the future (Figure S1). We overlaid hexagons of 5 km² on the potential sites to create planning units ($n = 5,457$).

SST predictions

We used three future scenarios: RCP8.5, RCP4.5, and RCP2.6 because they are a substantially rising, an intermediate, and peak and decline pathway, respectively (Moss *et al.* 2010). The Model for Interdisciplinary Research on Climate-Earth System Model (MIROC-ESM) was used to obtain the future SST. We used this model because it was developed by Japanese institutions and represents our study region well (Watanabe *et al.* 2011). The biases between the observed and the modeled values for the historical simulations from 1982 to 2005 were corrected by adding the anomaly of the model to the observed climatology using the method developed by Yara *et al.* (2011).

We considered three timeframes: current conditions, the near future, and the distant future. We used the 10-year SST average for February to estimate the SST values for these three timeframes (2010 to 2019 for current conditions, 2030 to 2039 for the near future, 2090 to 2099 for the distant future). We used February because it is the coldest month of the year, which is the main limiting factor for coral expansions to high latitudes (Veron & Minchin 1992).

Conservation features and targets

SST was shown as a reliable environmental predictor of marine biodiversity including corals (Tittensor *et al.* 2010; Sommer *et al.* 2013). Conservation features may include species, habitat types, and other mapable elements that represent biodiversity. We defined three conservation features representing coral community types for each of the three RCPs (nine conservation features in total) using the monthly-mean isothermal lines of 10°C, 13°C, and 18°C in the coldest months, developed by Yara *et al.* (2011) (Figure 1). These temperatures were chosen

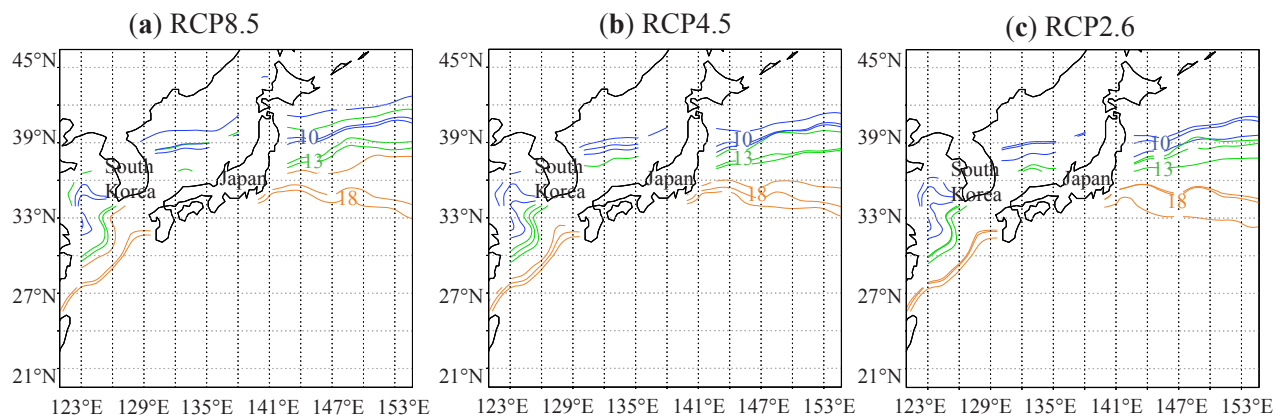


Figure 1 Sea-surface temperature (SST) predictions under (a) RCP8.5, (b) RCP4.5, and (c) RCP2.6 using a climate model, the Model for Interdisciplinary Research on Climate-Earth System Model (MIROC-ESM). SST values are the 10-year SST average for February for three time slices (2010 to 2019 for current conditions, 2030 to 2039 for the near future, 2090 to 2099 for the distant future). As time passes, the SST increases in all cases. The lowest monthly-mean isothermal lines represent the current conditions, middle lines the near future, the highest lines the distant future.

because the SST of 10°C is the limit of coral occurrence in Japan (Honma & Kitami 1978), and marginal coral communities were established where the average winter water temperature was approximately 13°C in Japan (Yamano *et al.* 2012). Further, we considered 18°C as the lower limit to establish the majority of tropical hard corals (Kleypas *et al.* 1999). We defined different temperature ranges as conservation features: “temperate” for 10–13°C, “subtropical” for 13–18°C, and “tropical” for 18–30°C (Figure 1). There were planning units in which the three temperature zones were predicted to change through time based on the projections (e.g., the physically same planning unit has “temperate” temperature zones in current conditions, but “subtropical” in the near future and “tropical” in the distant future)—we termed these planning units “transformation zones.” We put a focus on how these transformation zones perform in the selection of priorities because they differ depending on the RCP used. Conservation targets of 20% of the area were set, to ensure that 20% of the distribution of each conservation feature is included in the reserves.

Cost data

Although it would be ideal to use the spatial distribution of fishing effort or profit as a cost of establishing marine reserves, such information were not available to us. As a surrogate for fishing effort, we used population data in Japan as a proxy to estimate the lost opportunity, per Makino *et al.* (2014) and Klein *et al.* (2012). We used the population data predicted for every 5-year period until 2100 in Japan, based on the assumption that population will decrease at the same rate as seen in the

population census data during the years 2000 and 2005 (Project S-8, Environment Research and Technology Development Fund, Ministry of the Environment, Japan) (Figure S2). However, we understand that it is not likely that the population will decline at the same rate until the end of century. We calculated the average population size using the years of 2010, 2015, and 2020 for current conditions, years of 2030, 2035, and 2040 for near future, and years of 2090, 2095, and 2100 for distant future.

Spatial prioritization

We used the decision-support tool Marxan (<http://www.uq.edu.au/marxan/>), which minimizes costs while meeting predetermined conservation targets (Ball *et al.* 2009).

We considered spatial and temporal connections between planning units because it substantially increased the number of the planning units that were prioritized repeatedly over time, compared with a plan that ignored temporal connections (Makino *et al.* 2014). A planning unit can be: (1) connected to the adjacent planning units in the same time (spatial connections); (2) connected to itself at another time (temporal connections); and (3) connected to neighboring planning units in the future at three distances—nearest neighbors and neighbors that are two and three hexagon(s) away. We calculated the connectivity strength using the same methods described by Makino *et al.* (2014).

We set four cases based on which climate scenario was used for spatial prioritization: case 1 “RCP8.5”; case 2 “RCP4.5”; case 3 “RCP2.6”; and case 4 “all three RCPs.” In case 4, all nine conservation features (three conservation features for each of the three RCPs) were targeted to

ensure all conservation features are protected under any climate scenario.

We ran Marxan 100 times for each case. We conducted cluster analyses of Bray-Curtis dissimilarities with all solutions of all cases that use a single RCP to find most similar solutions between different cases (Linke *et al.* 2011).

Results

Differences among cases

The number of selected planning units was similar among all cases in the distant future (Table 1). When we planned using a single RCP (case 1–3), the overall reserve costs were 10–16% smaller than case 4 (planning using three RCPs) in the distant future (Table 1). The pessimistic RCP8.5 (case 1) had the smallest cost in both near and distant future. The differences in costs and the number of selected planning units among cases were slightly larger in the near future compared to those in the distant future (Table 1).

Differences in selection frequency (i.e., areas selected frequently throughout time) between cases were largest between cases 2 (RCP4.5) and 4, as measured by the sum of differences across all planning units (Figure 2). Cases 1 (RCP8.5) and 3 (RCP 2.6) had the most similar selection frequencies, where the sum of differences was approximately 56% less than between cases 2 and 4. These trends in differences in selection frequency throughout time were also seen in the reserve design in the near future.

Among the planning units that were selected more than 50 times at each time for all cases (termed high priority hereafter), less than half of them were in transformation zones (Table 2). Case 4 (all three RCPs) had approximately 46% of high priorities in the transformation zone (Table 2). Case 2 had the smallest number of planning units in transformation zone, less than half compared with other cases. The proportion of high priority planning units in the transformation zone was only 12% in case 2 (Table 2).

“No regrets” priority areas

Areas selected as “no regrets” priority areas (i.e., selected areas in case 4, areas that are consistently priorities for all three RCPs) were identified (Figure S3). In case 4, the number of selected planning units increased less than 1% compared to other cases (cases 1–3) (Table 1). However, the “no regrets” priority areas were not necessarily priorities in other cases. For any of the single RCP cases (cases 1–3) approximately 10% of “no regrets” priority areas were not selected at all.

Mismatch between the RCPs used in reserve design

The most similar solutions between cases that used a single RCP (i.e., a pair of solutions that had the lowest Bray-Curtis dissimilarities) were identified (Figures S4–S6). Although we found very similar solutions for different RCPs, no single RCP can meet all conservation targets for the other RCPs (Figure 3a–c). For example, the conservation feature “temperate zone” (10–13°C) in the distant future will be missed entirely if we planned using RCP4.5 or RCP2.6 and if the real trajectory were RCP8.5 (Figure 3a). When we planned for RCP8.5, but if the real trajectory were RCP4.5 or 2.6, the total losses in achieved conservation targets were largest through time, but they were smallest for only current conditions (Figure 3a).

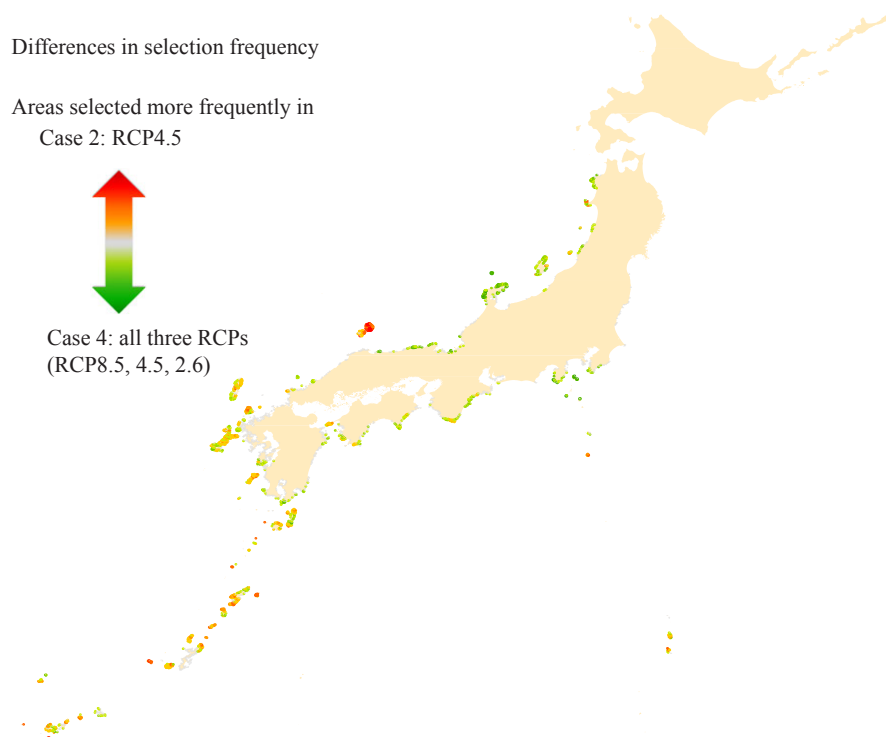
Discussion

Previous studies have emphasized the widespread need for consideration of future climate change in conservation planning (Araújo *et al.* 2004; Carvalho *et al.* 2011). We showed how size, cost, and spatial configuration of optimal reserve systems differ under three future climates and we identified “no regrets” priority areas (i.e., areas that consistently meet conservation targets across all three RCPs). These “no regrets” priority areas would be missed when we prioritize areas using a single RCP. Therefore, the best way to find priority areas robust to prediction uncertainty will be to use all available RCPs when planning.

We discovered that using the intermediate RCP4.5 (case 2) produced the most different reserve network compared to that produced by using multiple RCPs (case 4). This is because using RCP4.5 had the smallest number of planning units in transformation zones (i.e., the marginal areas where the three temperature zones were predicted to change through time based on the projections). Areas selected using RCP4.5 differed substantially from those that had more dramatic future changes (i.e., RCP8.5). If planning using multiple RCPs is not an option, then it is prudent to use the RCP8.5—the most extreme climate scenario. This is because it had the least overall costs (i.e., surrogate for fishing effort) and fewest missed conservation targets if the real trajectory were RCP4.5 or 2.6, because it has the largest number of planning units in transformation zones. However, if there is a particular conservation targets included criteria specific to stepwise range shifts, such as ensuring that marine reserves are positioned in the subtropical zone to support tropical to subtropical transitions, using RCP4.5 will have the fewest missed conservation targets of the “subtropical” temperature zone through time (until 2100).

Table 1 Comparison of costs and the number of selected planning units among four cases using the 10 best solutions (i.e., the reserve system with the 10 minimum score from 100 runs)

	Cost(sum of the population within 20km)		Number of selected planning units	
	Near future	Distant future	Near future	Distant future
1: RCP 8.5	12,764,340	14,169,448	1,527	2,293
2: RCP 4.5	13,147,810	14,580,690	1,536	2,311
3: RCP 2.6	13,455,705	14,874,256	1,539	2,316
4: all three RCPs	14,814,519	16,375,338	1,548	2,321

**Figure 2** Differences in selection frequency throughout time slices between case 2 “RCP4.5” and case 4 “all three RCPs.” Areas selected more frequently in case 2 are shown in red and in case 4 are in green.**Table 2** The number of planning units in transformation zones (i.e., the marginal areas where the three temperature zones change in time) and those selected more than 50 times at each time out of 100 solutions at each time (300 solutions in total)

Case	Total number of planning units in transformation zone	The number of planning units in transformation zone selected more than 50 times at each time	Total number of planning units that were selected more than 50 times at each time
1: RCP 8.5	2,499	287	685
2: RCP 4.5	934	86	714
3: RCP 2.6	1,146	273	675
4: all three RCPs	2,717	310	682

We recognize that our approach is simple and has limitations. We used the temperature zones as proxy for potential and existing coral habitats. We considered only the coldest month because coral expansions are limited by cold, while the upper temperature threshold of 31°C is relevant for coral bleaching and potential widespread

coral mortality (Donner 2009); such high temperatures and corresponding bleaching events are rarely observed at high latitudes (but see Harrison *et al.* (2011)). Both low and upper temperatures influence coral ecology including its physiology, traits, competition, and mortality (Sommer *et al.* 2013; Bates *et al.* 2014) and future

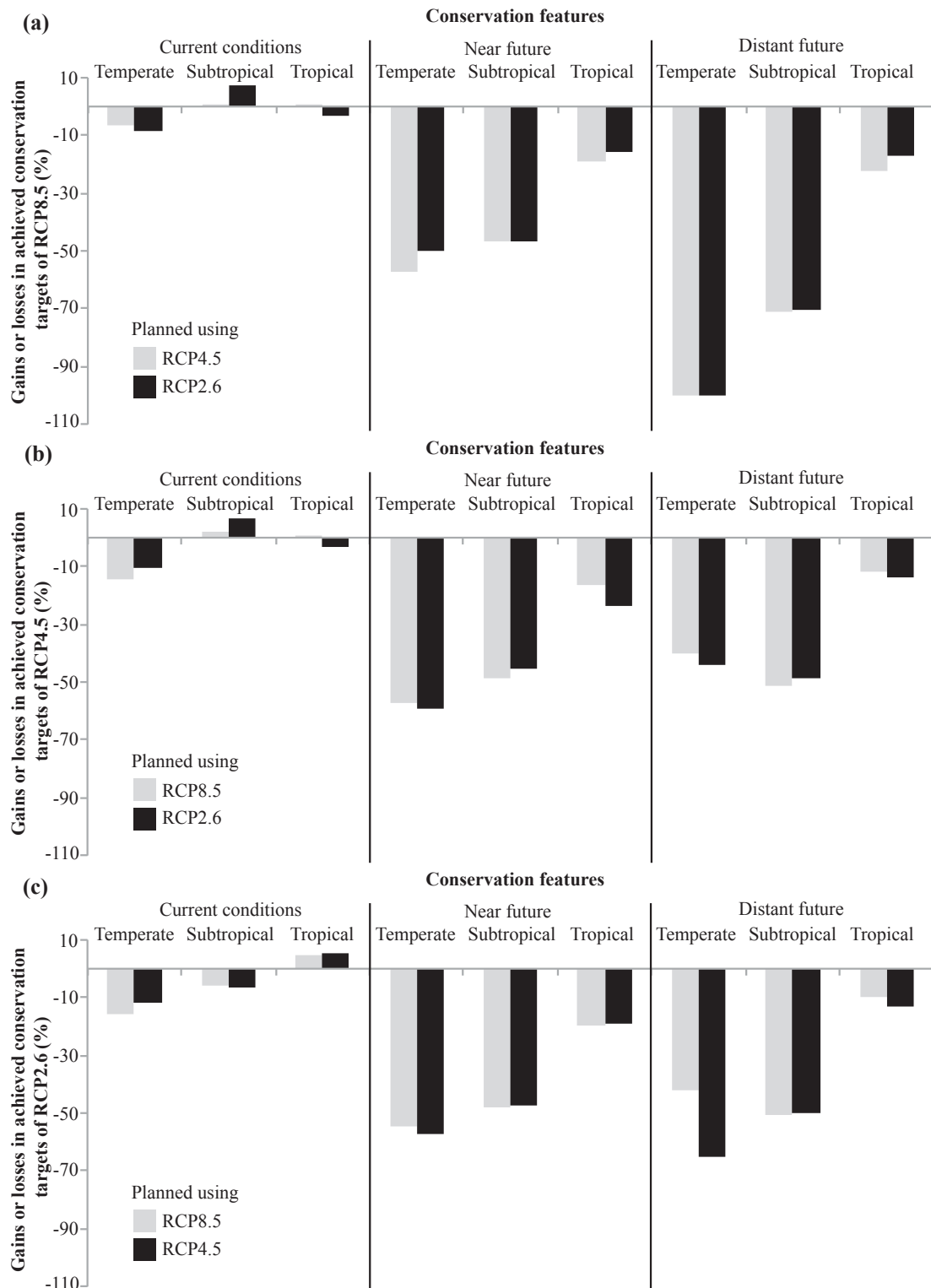


Figure 3 Gains or losses in achieved conservation targets of an RCP scenario when we plan using different RCP scenario using the most similar solutions between cases (i.e., a pair of solutions that had the lowest Bray-Curtis dissimilarities): conservation targets based on (a) RCP8.5, (b) RCP4.5, and (c) RCP2.6. When the conservation target was just achieved, the value is zero. For example, in Figure 33a, when we planned using RCP2.6, the conservation feature of “subtropical” in current conditions was met by exceeding the conservation targets of RCP8.5 approximately 7%, whereas the conservation feature of “temperate” in distant future met 0% of the conservation targets of RCP8.5 when planning using RCP4.5 or 2.6.

studies are required to plan for the rear edge of coral range shifts. Furthermore, research is needed to understand coral resilience, the rates of range shifts, coral community assembly, and the potential for adaptation to elevated SST (Hughes *et al.* 2012; Beger *et al.* 2014). We did not consider physical complexities such as currents and water quality. Increases in the velocity and extent of the Kuroshio current are anticipated (Sakamoto *et al.* 2005). Such changes affect long-distance dispersal (Trakhtenbrot *et al.* 2005) and eventually population connectivity (Munday *et al.* 2009). There are other threats to corals including ocean acidification, crown-of-thorns outbreaks, and fisheries (Burke *et al.* 2011). In addition, combined effects of SST rise and ocean acidification that are likely to be synergistic (Pardolfi *et al.* 2011; Brown *et al.* 2014). We used the best available data, but the differences in spatial scale between planning units and the global climate models limit our ability to predict fine-scale coral community distributions. More fine scale coastal climate predictions are a key element that would improve our results. We only used one climate model which represents our study region well (Watanabe *et al.* 2011). We acknowledge that different climate models are expected to result in different predictions but our focus was on the impact of different RCPs. Finally, coupled climate models to simulate present and future climate systems have inherent uncertainties (Reichler & Kim 2008); their effect was omitted in this study.

Results of this study provide evidence that the choice of climate scenario used in designing reserves will influence the success or failure of reserves. First and most importantly, we discovered there are “no regrets” areas that are always important to protect regardless of which climate projection we used. Second, we quantified the risk of underestimating or ignoring future changes when planning for the conservation of coral reefs, including inefficient allocation of limited conservation funding. Our findings could influence several global and national initiatives focused on implementing marine reserves. For example, it could help nations implement Aichi Biodiversity Targets 10 and 11 of the Convention on Biological Diversity, which states that multiple anthropogenic pressures on coral reefs should be minimized by 2015 and that at least 10% of coastal and marine areas should be protected by 2020. An action plan to conserve coral reef ecosystems in Japan was developed by the Ministry of Environment in 2010 (Ministry of Environment, Japan 2010 http://www.env.go.jp/nature/biodic/coralreefs/pamph/pamph_full-en.pdf), which includes designation of marine reserves. In 2014, The Japanese Coral Reef Society formed a task force to develop proposals for coral reefs conservation including establishment of marine reserves to the Ministry of Environment for the revision of the

action plan that our findings are relevant to. Further, this work could apply any other planning process where climate predictions are being used to inform decisions about marine reserve placement. One example, that neighbors Japan, is the Coral Triangle Initiative which is working toward implementing marine protected areas to protect the epicenter of coral reef biodiversity to incorporate multiple future climate predictions in their planning (<http://www.coraltriangleinitiative.org/>). Finally, our analysis reminds us that conservation decisions should be re-evaluated given new climate change projections. Our approach is applicable even in data limited places, thus it is relevant to marine reserve planners in any country.

Acknowledgments

This project was supported by the Australian Research Council (ARC) Centre of Excellence for Environmental Decisions (CEED). AM is funded by the ITO Foundation, Japan and by the ARC CEED, the University of Queensland. AM, HY, and YY are supported partially by Environment Research and Technology Development Fund, Ministry of the Environment, Japan (Project S-9). CJK is supported by an ARC Postdoctoral Fellowship (Project number DP110102153). MB is supported by a Discovery Early Career Research Award to the ARC CEED (CE110001014).

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Figure S1: The planning region, Japan, entails rocky areas within 1 km along the coastline shallower than 100 m as potential sites for coral range expansion in the future.

Figure S2: Estimated population for (a) current conditions, (b) the near future, and (c) the distant future.

Figure S3: Map of the “no regrets” priority areas (case 4 “all three RCPs”) based on the selection frequency of 100 solutions at each time (300 solutions in total).

Figure S4: Results of the cluster analyses of all solutions in case 1 “RCP8.5” (s1-s100) and 2 “RCP4.5” (s101–200). The higher Bray-Curtis dissimilarities, the more solutions differ.

Figure S5: Results of the cluster analyses of all solutions in case 1 “RCP8.5” (s1-s100) and 3 “RCP2.6” (s101–s200).

Figure S6: Results of the cluster analyses of all solutions in case 2 “RCP4.5” (s1-s100) and 3 “RCP2.6” (s101–s200).

References

- Araújo, M.B., Cabeza, M., Thuiller, W., Hannah, L., & Williams, P.H. (2004). Would climate change drive species out of reserves? An assessment of existing reserve-selection methods. *Global Change Biol.*, **10**, 1618-1626.
- Baird, A.H., Sommer, B., & Madin, J.S. (2012). Pole-ward range expansion of *Acropora* spp. along the east coast of Australia. *Coral Reefs*, **31**, 1063-1063.
- Ball, I.R., Possingham, H.P., & Watts, M. (2009). Marxan and relatives: software for spatial conservation prioritisation. Pages 185-195 in A. Moilanen, K.A. Wilson, & H.P. Possingham, editors. *Spatial conservation prioritisation: quantitative methods and computational tools*. Oxford University Press, Oxford, UK.
- Bates, A.E., Barrett, N.S., Stuart-Smith, R.D., Holbrook, N.J., Thompson, P.A., & Edgar, G.J. (2014). Resilience and signatures of tropicalization in protected reef fish communities. *Nat. Clim. Change*, **4**, 62-67.
- Beger, M., Sommer, B., Harrison, P.L., Smith, S.D.A., & Pandolfi, J.M. (2014). Conserving potential coral reef refuges at high latitudes. *Divers. Distrib.*, **20**, 245-257.
- Brown, C.J., Saunders, M.I., Possingham, H.P., & Richardson, A.J. (2014). Interactions between global and local stressors of ecosystems determine management effectiveness in cumulative impact mapping. *Divers. Distrib.*, **20**, 538-546.
- Burke, L., Reynter, K., Spalding, M., & Perry, A. (2011). Reefs at risk revisited. *World Resources Institute*, Washington, D.C., USA. 114p. Available: <http://www.wri.org/publication/reefs-risk-revisited>. Accessed 07 January 2014.
- Carvalho, S.B., Brito, J.C., Crespo, E.G., Watts, M.E., & Possingham, H.P. (2011). Conservation planning under climate change: toward accounting for uncertainty in predicted species distributions to increase confidence in conservation investments in space and time. *Biol. Conserv.*, **144**, 2020-2030.
- Deser, C., Phillips, A.S., & Alexander, M.A. (2010). Twentieth century tropical sea surface temperature trends revisited. *Geophys. Res. Lett.*, **37**, L10701, doi:10.1029/2010GL043321.
- Donner, S.D. (2009). Coping with commitment: projected thermal stress on coral reefs under different future scenarios. *PLoS ONE*, **4**, e5712.
- Frieler, K., Meinshausen, M., Golly, A. *et al.* (2013). Limiting global warming to 2°C is unlikely to save most coral reefs. *Nat. Clim. Change*, **3**, 165-170.
- Game, E.T., Watts, M.E., Wooldridge, S., & Possingham, H.P. (2008). Planning for persistence in marine reserves: a question of catastrophic importance. *Ecol. Appl.*, **18**, 670-680.
- Harrison, P.L., Dalton, S.J., & Carroll, A.G. (2011). Extensive coral bleaching on the world's southernmost coral reef at Lord Howe Island, Australia. *Coral Reefs*, **30**, 775-775.
- Honma, Y., & Kitami, T. (1978). Fauna and flora in the waters adjacent to the Sado Marine Biological Station, Niigata University. *Annu. Rep. Sado Marine Biol. Station*, **8**, 7-81.
- Hughes, T.P., Baird, A.H., Dinsdale, E.A. *et al.* (2012). Assembly rules of reef corals are flexible along a steep climatic gradient. *Curr. Biol.*, **22**, 736-741.
- Klein, C.J., Jupiter, S.D., Selig, E.R. *et al.* (2012). Forest conservation delivers highly variable coral reef conservation outcomes. *Ecol. Appl.*, **22**, 1246-1256.
- Kleypas, J.A., McManus, J.W., & Menez, L.A.B. (1999). Environmental limits to coral reef development: where do we draw the line? *Am. Zoologist*, **39**, 146-159.
- Levy, J.S., & Ban, N.C. (2013). A method for incorporating climate change modelling into marine conservation planning: an Indo-west Pacific example. *Mar. Policy*, **38**, 16-24.
- Linke, S., Watts, M., Stewart, R., & Possingham, H.P. (2011). Using multivariate analysis to deliver conservation planning products that align with practitioner needs. *Ecography*, **34**, 203-207.
- Makino, A., Yamano, H., Beger, M., Klein, C.J., & Yara, Y., Possingham, H.P. (2014). Spatio-temporal marine conservation planning to support high-latitude coral range expansion under climate change. *Divers. Distrib.*, **20**, 859-871.
- McLeod, E., Moffitt, R., & Timmermann, A. *et al.* (2010). Warming seas in the Coral Triangle: coral reef vulnerability and management implications. *Coast. Manage.*, **38**, 518-539.
- Moss, R.H., Edmonds, J.A., Hibbard, K.A. *et al.* (2010). The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747-756.
- Mumby, P.J., Elliott, I.A., Eakin, C.M. *et al.* (2011). Reserve design for uncertain responses of coral reefs to climate change. *Ecol. Lett.*, **14**, 132-140.
- Munday, P.L., Leis, J.M., Lough, J.M. *et al.* (2009). Climate change and coral reef connectivity. *Coral Reefs*, **28**, 379-395.
- Pandolfi, J.M., Connolly, S.R., Marshall, D.J., & Cohen, A.L. (2011). Projecting coral reef futures under global warming and ocean acidification. *Science*, **333**, 418-422.
- Peters, G.P., Andrew, R.M., Boden, T. *et al.* (2013). The challenge to keep global warming below 2 [deg]C. *Nat. Clim. Change*, **3**, 4-6.
- Precht, W.F., & Aronson, R.B. (2004). Climate flickers and range shifts of reef corals. *Front. Ecol. Environ.*, **2**, 307-314.
- Pressey, R.L., & Bottrill, M.C. (2009). Approaches to landscape- and seascape-scale conservation planning: convergence, contrasts and challenges. *Oryx*, **43**, 464-475.
- Reichler, T., & Kim, J. (2008). How well do coupled models simulate today's climate? *Bull. Am. Meteorol. Soc.*, **89**, 303-311.
- Sakamoto, T.T., Hasumi, H., Ishii, M. *et al.* (2005). Responses of the Kuroshio and the Kuroshio Extension to global warming in a high-resolution climate model. *Geophys. Res. Lett.*, **32**, L14617.
- Sommer, B., Harrison, P.L., Beger, M., & Pandolfi, J.M. (2013). Trait-mediated environmental filtering drives assembly at biogeographic transition zones. *Ecology*, **95**, 1000-1009.

- Tittensor, D.P., Mora, C., Jetz, W. *et al.* (2010). Global patterns and predictors of marine biodiversity across taxa. *Nature*, **466**, 1098–1101.
- Trakhtenbrot, A., Nathan, R., Perry, G., & Richardson, D.M. (2005). The importance of long-distance dispersal in biodiversity conservation. *Divers. Distrib.*, **11**, 173–181.
- van Hooidonk, R., Maynard, J.A., & Planes, S. (2013). Temporary refugia for coral reefs in a warming world. *Nat. Clim. Change*, **3**, 508–511.
- Veron, J.E.N., & Minchin, P.R. (1992). Correlations between sea surface temperature, circulation patterns and the distribution of hermatypic corals of Japan. *Cont. Shelf Res.*, **12**, 835–857.
- Warren, R., VanDerWal, J., Price, J. *et al.* (2013). Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nat. Clim. Change*, **3**, 678–682.
- Watanabe, S., Hajima, T., Sudo, K. *et al.* (2011). MIROC-ESM: model description and basic results of CMIP5–20c3m experiments. *Geosci. Model Dev.*, **4**, 1063–1128.
- Yamano, H., Sugihara, K., Nomura, K. (2011). Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures. *Geophys. Res. Lett.*, **38**, L04601.
- Yamano, H., Sugihara, K., Watanabe, T., Shimamura, M., & Hyeong, K. (2012). Coral reefs at 34°N, Japan: exploring the end of environmental gradients. *Geology*, **40**, 835–838.
- Yara, Y., Oshima, K., Fujii, M., Yamano, H., Yamanaka, Y., & Okada, N. (2011). Projection and uncertainty of the poleward range expansion of coral habitats in response to sea surface temperature warming: a multiple climate model study. *Galaxea, J. Coral Reef Stud.*, **13**, 11–20.