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

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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...
Effect of climate scenarios on reserve design
A. Makino et al.

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)

| Case | Cost (sum of the population within 20km) Near future | Cost (sum of the population within 20km) Distant future | Number of selected planning units Near future | Number of selected planning units 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 |

Differences in selection frequency

Areas selected more frequently in Case 2: RCP4.5

Case 4: all three RCPs (RCP8.5, 4.5, 2.6)

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 3a, 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 (Pandolfi 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/pamphfull-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.

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 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 2 “RCP4.5” (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).
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