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Title:

Meeting fisheries, ecosystem function, and biodiversity goals in a human dominated world

One sentence summary: Simultaneously meeting fisheries, ecosystem function, and biodiversity goals for coral reefs is possible through strategically placed marine reserves and fisheries restrictions.

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Abstract:

The worldwide decline of coral reefs necessitates targeting management solutions that can sustain reefs and the livelihoods of the people who depend on them. Yet little is known about the context in which different reef management tools can help to achieve multiple social and ecological goals. Due to non-linearities in the likelihood of achieving combined fisheries, ecological function, and biodiversity goals along a gradient of human pressure, relatively small changes in the context where management is implemented could have dramatic impacts on whether these goals are likely to be met or not. Critically, management can provide substantial conservation benefits to

the majority of reefs for fisheries and ecological function, but not biodiversity goals, given their degraded state and the levels of human pressure they face.

Main Text:

At the forefront of ongoing efforts to sustain coral reef ecosystems in the current period of intense social and environmental change is an increasing need to simultaneously manage for multiple goals, including fisheries, ecosystem functioning, and biodiversity (*1*, *2*). Yet, critical gaps remain in our capacity to effectively implement this type of ecosystem-based management approach, where multiple goals are simultaneously pursued (*3*). In particular, little is known about: (i) the context under which key goals can be simultaneously met, and (ii) the degree to which local management efforts can help to meet them.

Here, we compiled data from ~1800 tropical reef sites across 41 countries, states, and territories to examine the conditions under which reefs simultaneously support three ecological metrics reflecting key fisheries, ecological function, and biodiversity goals (*4*)(Fig. 1, Tables S1-2). These are, respectively: (1) potential stocks available for multi-species coral reef fisheries, calculated as the biomass of fishes >20 cm total length (*4*)(Fig. 1,

Table S2); (2) scraping potential, reflecting a unique ecological function performed by parrotfish that is critical for the removal of algal biomass and the provision of bare substrate for coral settlement (*4*, *5*) (Table S2); and (3) the diversity of species traits (i.e. home range, body size, diet, diurnal activity, schooling behavior, position in the water column), which can underpin aspects of biodiversity such as community assembly processes, ecosystem productivity, and stability (*6*). We measured trait diversity using a generalization of the Shannon entropy index accounting for both the dissimilarity of trait values present in a reef fish community and the spread of biomass across these trait values (*4*, *7*) (Table S2). Our analysis shows that the three metrics are not strongly related to each other (r<0.54; Fig S1).

To elucidate the capacity of reefs to simultaneously support multiple goals, we first developed reference conditions for each metric to serve as benchmarks. Reference conditions (also called reference points) are a key concept in fisheries and conservation (*8*, *9*), but are nascent in coral reef science (*10*). As key reference conditions, we used the top 10% value for each metric (corrected for sampling), but also included additional reference conditions (i.e. the top 5% and 20%) in the supplementary materials (*4*). We then set aspirational targets of 25, 50, and 75% of reference conditions. When looking at these aspirational targets across multiple goals, we found that only 5% of reef sites simultaneously had fish biomass, parrotfish scraping, and trait diversity at 75% of reference conditions (Fig. 1D). These sites, though reasonably rare, were geographically spread through the Indian, Pacific, and Atlantic ocean basins (Fig 1D). We found that 12.5% of sites simultaneously met the 50% target, and 29.3% of sites met the 25% target (Fig. 1D)

To examine the context under which key goals can be met, we first developed a series of Bayesian hierarchical models that quantify how the three ecological metrics are related to key socioeconomic drivers of resource exploitation, while controlling for environmental conditions and sampling techniques (4, 11, 12)(Fig. S2; Table S3). We then used the posterior distributions from these models to calculate how the probability of simultaneously meeting multiple goals changes along a gradient of human pressure, while holding other covariates constant (4) (Fig. 2, S3, S4). We measured human pressure as the size of human populations in the surrounding seascape divided by the accessibility (in minutes of travel time squared) of our reef sites to them - an adaptation of the economic gravity model used to measure the ‘gravitational pull’ of interactions such as trade and migration (4, 13). Human pressure displayed the most consistent negative relationships to our response variables

(Fig. S2). The distribution of human pressure and other key socioeconomic and environmental covariates among our surveyed reefs closely matches that of reefs globally (Fig. S5). The probability of openly fished reef sites simultaneously having all three metrics declined with our measure of human pressure and the ambitiousness of the conservation target (Fig. 2A). In other words, on openly fished reefs it is extremely unlikely that all three goals will be simultaneously met where human pressure is intense, but this likelihood increases where human pressure is low, particularly for the 25% and 50% targets. There was considerable variability in how the probability of meeting individual goals changed along a gradient of human pressure (Fig. 2B-D).

A critical gap remains in understanding the context in which different local management tools can help to simultaneously achieve key goals (*14*, *15*). To address this, we first examined the probability of reef sites in both fully protected Marine Protected Areas (MPAs) (where fishing is prohibited) and restricted fishing areas (where there are limitations on fishing gears used and who can access the fishing grounds) in achieving key targets for the individual and combined ecological metrics (Fig 2E-L). We then calculated the 'conservation gains' from employing these different forms of management along a gradient of human pressure (*15*) (Fig. 2M-X). By conservation gain, we refer to the difference in probability of achieving a specific target (e.g. 25% of reference condition biomass) when fully protected MPAs or fishery restrictions are implemented relative to openly fished areas. This concept gets at the idea that contexts with maximal conservation gains highlight the best opportunities for management to have the biggest impact; conversely, implementing management in contexts with minimal conservation gains (either because goals are already being met or because they are unlikely to be met regardless of management) provides few returns for limited conservation resources (*16*).

Critically, we find that both fully protected MPAs and restricted fishing areas have the potential to provide conservation gains, but the context under which these gains can be maximized is highly variable depending on both the goal and target (Fig. 2M-X). For simultaneously meeting fisheries, function, and biodiversity, maximal conservation gains are from fully protected MPAs in the lowest human pressure locations for the most ambitious target (75% of reference conditions), but as targets become less ambitious, conservation gains peak where human pressure is more intermediate (Fig. 2M). For all three targets, there are minimal conservation gains in locations where human pressure is most intense, which means that in this context, management is unlikely to help meet these goals. For each independent goal, the context under which conservation gains can be maximized varies considerably (Fig 2). Of note is that trait diversity is the least responsive to management, with conservation gains never reaching above 0.4.

We then simulated how the number of our openly fished sites achieving key conservation targets would change if a fully protected MPA (Fig. 3) or fisheries restrictions (Fig S6) were implemented, given the other conditions at our reef sites. Our analysis reveals both key opportunities and constraints in the capacity for local management to simultaneously meet multiple goals. On one hand, for more than 50% of our fished sites, the implementation of a fully protected MPA is predicted to help achieve multiple goals (Fig. 3A). On the other hand, less than 1% of the sites starting below 25% of reference conditions are predicted to achieve the 75% of reference conditions target, highlighting how the broader seascape context may stunt MPA potential in degraded reefs (*15*). Indeed, more than half of the 87.4% of openly fished reefs starting below 25% of reference conditions are predicted to remain in the that same category (Fig 3A). Additionally, our analysis shows that even where fishable biomass is very low, scraping potential and trait diversity are often >25% of reference conditions (Fig. 3B-D); a finding supported by previous research showing that herbivores and a diversity of traits can still persist on degraded reefs (*17*).

In situations where fishing prohibitions are in direct conflict with achieving certain fisheries goals, other forms of management may be necessary (*18*). We found that fisheries restrictions provide a similar pattern, but typically lower magnitude, of conservation gains than fully protected MPAs, particularly for achieving the combined goal and fisheries goal (Fig 2Q-X, Fig S6). Of note is that for parrotfish scraping potential, fishing restrictions provide the same conservation gains as MPAs, providing multiple ways to achieve that specific goal (Fig. 2W).

Together, our findings provide guidance on what can be realistically achieved with various forms of local management regarding key fisheries, ecological function, and biodiversity goals on coral reefs. We highlight key pros and cons of placing management in different areas by demonstrating how potential conservation gains vary not only by goal, but also are strongly dependent on both the ambitiousness of the target and the context (Fig. 2, S3, S4). In particular, the potential for local management to help in meeting goals is strongly related to the amount of human pressure in the surrounding seascape (Fig. 2, *S*2). A key finding is that conservation gains tend to change non-linearly with human pressure, which means that relatively small changes in the context where management is implemented could have big impacts on whether key goals are likely to be met (Fig. 2M-X). This not only has important implications for the placement of new MPAs, but is also relevant to how future socioeconomic changes, such as infrastructure development and population growth may impact the efficacy of reef conservation. However, the impacts of these changes could potentially be buffered by making management more effective, for example, by leveraging insights about using social norms and cognitive biases to improve compliance (*19*, *20*) and learning lessons about key practices and processes from locations that have defied expectations of global reef degradation (*12*, *21*). Our global analysis makes clear the limitations of local management, especially in promoting certain aspects of biodiversity like trait diversity. While international action on climate change will be crucial for ensuring a future for coral-dominated reefs (*1, 2*), effective management will also be critical to sustaining reefs and the millions of livelihoods that depend on them.

References and Notes

1. T. P. Hughes et al., Coral reefs in the Anthropocene. Nature. **546**, 82–90 (2017).
2. A. V Norström et al., Guiding coral reef futures in the Anthropocene. Front. Ecol. Environ. **14**, 490–498 (2016).
3. E. K. Pikitch et al., Ecosystem-based fishery management. Science. **305**, 346–347 (2004).
4. Materials and methods are available as supplementary materials at the Science website.
5. Y.-M. Bozec et al., Tradeoffs between fisheries harvest and the resilience of coral reefs. Proc. Natl. Acad. Sci. **113**, 4536–4541 (2016).
6. J. E. Duffy et al., Biodiversity enhances reef fish biomass and resistance to climate change. Proc. Natl. Acad. Sci. **113**, 6230–6235 (2016).
7. A. Chao et al., An attribute-diversity approach to functional diversity, functional beta diversity, and related (dis)similarity measures. Ecol. Monogr. **89**, e01343 (2019).
8. M. A. MacNeil, The politics, science and policy of reference points for resource management. Environ. Conserv. **40**, 297–301 (2013).
9. G. M. Mace, R. Lande, Assessing Extinction Threats: Toward a Reevaluation of IUCN Threatened Species Categories. Conserv. Biol. **5**, 148–157 (1991).
10. T. R. McClanahan et al., Critical thresholds and tangible targets for ecosystem-based management of coral reef fisheries. Proc. Natl. Acad. Sci. **108**, 17230–17233 (2011).
11. H. J. Geist, E. F. Lambin, Proximate Causes and Underlying Driving Forces of Tropical Deforestation. Bioscience. **52**, 143–150 (2002).
12. J. E. Cinner et al., Bright spots among the world’s coral reefs. Nature. **535**, 416–419 (2016).
13. J. E. Anderson, The Gravity Model. Annu. Rev. Econom. **3**, 133–160 (2011).
14. R. S. Steneck et al., Attenuating effects of ecosystem management on coral reefs. Sci. Adv. **4**, eaao5493 (2018).
15. J. E. Cinner et al., Gravity of human impacts mediates coral reef conservation gains. Proc. Natl. Acad. Sci. **115**, E6116–E6125 (2018).
16. P. J. Ferraro, S. K. Pattanayak, Money for nothing? A call for empirical evaluation of biodiversity conservation investments. PLoS Biol. **4**, e105 (2006).
17. J. P. W. Robinson et al., Productive instability of coral reef fisheries after climate-driven regime shifts. Nat. Ecol. Evol. **3**, 183–190 (2019).
18. R. Hilborn et al.,When can marine reserves improve fisheries management? Ocean Coast. Manag. **47**, 197–205 (2004).
19. B. J. Bergseth, M. Roscher, Discerning the culture of compliance through recreational fisher’s perceptions of poaching. Mar. Policy. **89**, 132–141 (2018).
20. J. Cinner, How behavioral science can help conservation. Science. **362**, 889-890 (2018).
21. G. Post, J. Geldmann, Exceptional responders in conservation. Conserv. Biol. **32**, 576–583 (2018).
22. Cinner, J. (2020): Data from: Meeting fisheries, ecosystem function, and biodiversity goals in a human dominated world. James Cook University. (dataset). http://dx.doi.org/10.25903/5e61a7f08ae39. DOI: 10.25903/5e61a7f08ae39
23. J. Zamborain-Mason. Code for Meeting fisheries, ecosystem function, and biodiversity goals in a human dominated world. JZamborain-Mason/Cinneretal_2020_multiplegoals. Zenodo. DOI: 10.5281/zenodo.3697928

24. T. M. Daw et al., The spatial behaviour of artisanal fishers: Implications for fisheries management and development (Fishers in Space). Final Report (2011).
25. R. Froese, D. Pauly, FishBase (2015), (available at http://www.fishbase.org).
26. A. S. Hoey, D. R. Bellwood, Limited Functional Redundancy in a High Diversity System: Single Species Dominates Key Ecological Process on Coral Reefs. Ecosystems. **12**, 1316–1328 (2009).
27. R. M. Bonaldo, A. S. Hoey, D. R. Bellwood, Oceanography and Marine Biology (CRC Press, 2014; https://www.taylorfrancis.com/books/9781482220667), vol. 52.
28. R. M. Bonaldo, D. R. Bellwood, Size-dependent variation in the functional role of the parrotfish Scarus rivulatus on the Great Barrier Reef, Australia. Mar. Ecol. Prog. Ser. **360**, 237–244 (2008).
29. L. Ong, K. N. Holland, Bioerosion of coral reefs by two Hawaiian parrotfishes: species, size differences and fishery implications. Mar. Biol. **157**, 1313–1323 (2010).
30. J. H. Bruggemann et al., Bioerosion and sediment ingestion by the caribbean parrotfish Scarus vetula and Sparisoma viride: Implications of fish size, feeding mode and habitat use. Mar. Ecol. Prog. Ser. **134**, 59–71 (1996).
31. D. Mouillot et al., Functional over-redundancy and high functional vulnerability in global fish faunas on tropical reefs. Proc. Natl. Acad. Sci. **111**, 13757–13762 (2014).
32. C. Mora, Coral Reefs and the Global Network of Marine Protected Areas. Science. **312**, 1750–1751 (2006).
33. C. I. E. S. I. Network, “Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11” (Palisades, NY, 2015), doi:10.7927/H4JW8BX5.
34. M. A. MacNeil, S. R. Connolly, Multi-scale patterns and processes in reef fish abundance. in C. Mora ed. Ecology of Fishes on Coral Reefs. (Cambridge, 2015). pp. 116–126.
35. J. E. Anderson, A theoretical foundation for the gravity equation. Am. Econ. Rev. **69**, 106–116 (1979).
36. E. G. Ravenstein, The Laws of Migration. J. Stat. Soc. London. **48**, 167 (1885).
37. E. A. Bright, P. R. Coleman, A. N. Rose, M. L. Urban, LandScan. Oak Ridge Natl. Lab. (2012).
38. E. Maire et al., How accessible are coral reefs to people? A global assessment based on travel time. Ecol. Lett. **19**, 351–360 (2016).
39. D. Pauly, D. Zeller, Sea Around Us Concepts, Design and Data (2015), (available at http://www.seaaroundus.org).
40. UNEP-WCMC, Global distribution of warm-water coral reefs (2010), (available at http://data.unep-wcmc.org/datasets/1).
41. J. M. Gove et al., Quantifying Climatological Ranges and Anomalies for Pacific Coral Reef Ecosystems. PLoS One. **8**, e61974 (2013).
42. J. Maina et al., Global Gradients of Coral Exposure to Environmental Stresses and Implications for Local Management. PLoS One. **6**, e23064 (2011).
43. The World Bank (2015), (available at http://www.govindicators.org).
44. P. C. Bürkner, brms: An R package for Bayesian multilevel models using Stan. J. Stat. Softw. (2017), doi:10.18637/jss.v080.i01.
45. A. Vehtari, A. Gelman, J. Gabry, Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. Stat. Comput. **27**, 1433 (2017).
46. N. C. Krueck et al., Incorporating larval dispersal into MPA design for both conservation and fisheries. Ecol. Appl. **27**, 925–941 (2017).

47. T. R. McClanahan et al., Global baselines and benchmarks for fish biomass: Comparing remote reefs and fisheries closures. Mar. Ecol. Prog. Ser. **612**, 167–192 (2019).
48. B. Worm et al., Rebuilding Global Fisheries. Science. **325**, 578–585 (2009).
49. S. M. W. Reddy, A. Wentz, O. Aburto-Oropeza, M. Maxey, S. Nagavarapu, H. M. Leslie, Evidence of market-driven size-selective fishing and the mediating effects of biological and institutional factors. Ecol. Appl. **23**, 726–741 (2013).
50. N. K. Dulvy, R. P. Freckleton, N. V. C. Polunin, Coral reef cascades and the indirect effects of predator removal by exploitation. Ecol. Lett. **7**, 410–416 (2004).
51. D. R. Bellwood, A. S. Hoey, T. P. Hughes, Human activity selectively impacts the ecosystem roles of parrotfishes on coral reefs. Proc. R. Soc. B Biol. Sci. **279**, 1621–1629 (2012).
52. G. J. Edgar et al., Global conservation outcomes depend on marine protected areas with five key features. Nature. **506**, 216–220 (2014).
53. T. P. Hughes et al., Phase Shifts, Herbivory, and the Resilience of Coral Reefs to Climate Change. Curr. Biol. **17**, 360–365 (2007).
54. R. D. Stuart-Smith et al., Integrating abundance and functional traits reveals new global hotspots of fish diversity. Nature. **501**, 539–542 (2013).
55. G. D. Tilman, The Influence of Functional Diversity and Composition on Ecosystem Processes. Science. **277**, 1300–1302 (1997).
56. N. Gross et al., Functional trait diversity maximizes ecosystem multifunctionality. Nat. Ecol. Evol. **1**, 132 (2017).
57. S. Díaz, M. Cabido, Vive la différence: plant functional diversity matters to ecosystem processes. Trends Ecol. Evol. **16**, 646–655 (2001).
58. S. D’Agata et al., Marine reserves lag behind wilderness in the conservation of key functional roles. Nat. Commun. **7**, 12000 (2016).
59. D. Mouillot et al., A functional approach reveals community responses to disturbances. Trends Ecol. Evol. **28**, 167–177 (2013).

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Supplementary Materials

Materials and Methods

Table S1 – S7
Fig S1 – S4
References (24 – 59)

Figure Legends

Figure 1| Meeting multiple goals on coral reefs. The distribution of (A) biomass of reef fish >20cm (n=1798), (B) parrotfish scraping potential (n=1662), and (C) trait diversity (n=1662), all in natural log and corrected for sampling (*4*). Differences in the number of sites are because one data provider collected data at the family level, which could not be used in calculating parrotfish scraping potential or trait diversity. Parrotfishes were not detected at 31% of our reef sites (Fig. S1). (D) Sites that simultaneously have fish biomass, parrotfish scraping potential, and trait diversity at >75% (purple), 50-75% (dark pink), 25-50% (light pink), and <25% (black) of reference conditions (*4*). Points are jittered to allow for visualization of overlapping reef sites.

Figure 2 | The estimated probability of openly fished reef sites having 25, 50, and 75% of reference conditions (light, medium, and dark purple, respectively). (A) a combination of fish biomass (>20cm), parrotfish scraping potential, trait diversity, and (B-D) each metric, respectively, along a gradient of human pressure (gravity). Separate estimates are provided for reef sites in fully protected Marine Protected Areas (MPAs) where fishing is prohibited (E-H) and with restricted fishing (I-L). To highlight how the potential benefits of management change along a gradient of human pressure (gravity), we extracted the difference in the probability of achieving each target between MPAs and openly fished sites (M-P), restricted and openly fished areas (Q-T), and MPAs and restricted areas (U-X). We plotted the partial effect of the relationship between gravity and each target by setting all other continuous covariates to 0 (because they were all standardized) and all categorical covariates to their most common category (i.e. 4-10m for depth, slope for habitat, standard belt transect for census method). Gravity (x axis) is standardized, with an average of 0.

Fig. 3| Conservation target outcomes from simulating the implementation of fully protected Marine Protected Areas (MPAs) in openly fished sites. Alluvial plots show the change in the number of sites expected to achieve key conservation targets if MPAs were implemented in our openly fished sites for (A) simultaneously meeting fish biomass, parrotfish scraping potential, and trait diversity, and (B-D) each goal, respectively. The left hand side of each plot shows the current conditions and the right hand side shows the expected conditions if MPAs were implemented. Black <25%, light pink =25-50%, dark pink=50-75%, and purple >75% of reference conditions.