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The global costs and benefits of expanding Marine Protected Areas

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The global costs and benefits of expanding Marine Protected Areas

Abstract

Marine ecosystems and the services they provide contribute greatly to human well-being but are becoming degraded in many areas around the world. The expansion of Marine Protected Areas (MPAs) has been advanced as a potential solution to this problem but their economic feasibility has hardly been studied. We conduct an economic assessment of the costs and benefits of six scenarios for the global expansion of MPAs. The analysis is conducted at a high spatial resolution, allowing the estimated costs and benefits to reflect the ecological and economic characteristics and context of each MPA and marine ecosystem. The results show that the global benefits of expanding MPAs exceed their costs by a factor 1.4–2.7 depending on the location and extent of MPA expansion. Targeting protection towards pristine areas with high biodiversity yields higher net returns than focusing on areas with low biodiversity or areas that have experienced high human impact.

Keywords: Marine Protected Areas; global expansion scenarios; ecosystem services; cost-benefit analysis

61
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63 **1. Introduction**
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66 In response to increasing degradation of the marine environment and declining
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68 provision of ecosystem services, several national and international initiatives have
69
70 called for the development of Marine Protected Areas (MPAs) (CBD, 2010). An MPA is
71
72 a clearly defined geographical space, dedicated and managed, through legal or other
73
74 effective means, to achieve the long-term conservation of nature with associated
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76 ecosystem services and cultural values (IUCN, 2008). MPAs can improve the condition
77
78 of marine ecosystems through diverse ecological pathways and, although challenging
79
80 to quantify (Fox et al. 2014), result in improved biological parameters such as habitat
81
82 complexity, survival rates of juvenile fish, species diversity, fish biomass, density and
83
84 size (Lester et al., 2009). Improved ecosystem condition may translate into improved
85
86 provision of ecosystem services, particularly in terms of tourism and recreation
87
88 (Badalamenti et al., 2000; Potts et al. 2014), fisheries in adjacent areas through spill
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90 over effects (Roberts et al., 2001; Gell and Roberts, 2003) and cultural values
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92 associated with the conservation of marine biodiversity and mega-fauna (Cañadas et
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94 al., 2005).
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99
100 Currently, 4.8% of global marine area is designated as MPA, with approximately 2.2%
101
102 established as no-take MPAs (Atlas of Marine Protection, 2019). The location of
103
104 existing MPAs is represented in Figure 2. The two predominant statements calling for
105
106 the global expansion of networks of MPAs are the Convention on Biological Diversity
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108 (CBD) Aichi Target 11 and the Durban Action Plan developed at the 2003 Vth IUCN
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110 World Parks Congress, which call for an expansion of MPA coverage to 10% and 30%
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112 of global marine area respectively.
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123 Progress towards meeting the Aichi and Durban Targets has been made but
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125 considerably more investment is required to ensure the effectiveness and ecological
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127 representativeness of MPAs, in addition to their geographic coverage (Dunn et al,
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129 2014; Fox et al., 2014; Edgar et al., 2014, Boonzaier and Pauly, 2016; Gill et al., 2017).
130
131 Moreover, political support for meeting the Durban and Aichi Targets might be
132
133 increased by providing better information about the societal and economic relevance
134
135 of MPAs. MPAs may be viewed by some decision makers primarily as ecological
136
137 reserves rather than as assets that generate multiple services such as food, coastal
138
139 protection, carbon sequestration, genetic material and recreational opportunities
140
141 (Beaumont et al., 2007; Böhnke-Henricks et al., 2013). These services have high
142
143 economic values in terms of their contribution to specific sectors of the economy such
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145 as fisheries and tourism and also as non-marketed constituents of human well-being
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147 (Costanza et al., 1997; de Groot et al., 2012).
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152
153 The contribution of this study is to estimate the global costs and benefits of increasing
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155 no-take MPA coverage to evaluate the economic case for expanding MPAs. Earlier
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157 studies have examined the financial costs of establishing and operating MPAs
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159 (Balmford et al., 2004; McCrea-Strub et al., 2011), and the benefits of closing the high
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161 seas to fishing (White and Costello, 2014), but this study is the first to compare the
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163 economic costs and benefits of MPA expansion worldwide. On the cost side, the
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165 assessment includes the costs of establishing and operating MPAs, and the
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167 opportunity costs to commercial fisheries. On the benefit side, the marine ecosystems
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169 included in the assessment are coral reefs, coastal wetlands and mangroves; and the
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171 marine ecosystem services assessed are the provision of food and other materials for
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173 subsistence or commercial use; tourism and recreation; coastal protection;
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183 biodiversity; and carbon sequestration. This framing and assessment of the costs and
184
185 benefits of expanding MPAs is intended to inform and motivate on-going discussions
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187 on global coverage and placement of MPAs, including the development of a new
188
189 strategy for the Convention on Biological Diversity for the period 2021-2030.
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193 This assessment of the global costs and benefits of MPA expansion applies value
194
195 transfer methods (Johnston et al., 2015) in which information from existing studies on
196
197 MPA costs and ecosystem service values are transferred and scaled up across marine
198
199 areas that are protected by additional (hypothetical) MPAs under alternative future
200
201 scenarios. Using value transfer methods is arguably the only viable means of
202
203 estimating ecosystem service values at a global scale (Brander et al., 2012a; Costanza
204
205 et al., 2014) but this approach is characterised by several limitations and potential
206
207 inaccuracies (Rosenberger and Stanley, 2006). A potentially important source of
208
209 inaccuracy is so-called 'generalisation error', which occurs when values for study sites
210
211 are transferred to policy sites that are different without fully accounting for those
212
213 differences (Rosenberger and Phipps, 2007). The present study applies a multi-
214
215 disciplinary approach to explicitly account for spatial heterogeneity in ecological and
216
217 economic conditions in the estimation of MPA costs and benefits.
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220
221 The structure of the remainder of the paper is as follows: Section 2 describes the
222
223 methods applied in the analysis, including the overall methodological framework,
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225 scenario development, cost estimation, benefit estimation, cost-benefit analysis, and
226
227 sensitivity analysis; Section 3 present the results in the form of mapped scenarios for
228
229 MPA expansion, monetary values of costs and benefits for each scenario, output
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231 statistics for the cost-benefit analysis, and a sensitivity analysis of the results to
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243 variation in key parameters; Section 4 discusses the main results, uncertainties and
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245 limitations of the analysis; and Section 5 provides conclusions.
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247

248 **2. Methods**

249 **2.1 Methodological framework**

252
253 The methodological framework for the analysis combines data, methods and insights
254
255 from multiple disciplines including marine geography, biology, management and
256
257 economics. The framework broadly follows the ecosystem services approach (Kumar,
258
259 2012) and incorporates several critical insights from the environmental economics
260
261 literature by: contrasting counterfactual scenarios that differ solely in whether they
262
263 include policy interventions (Hussain et al., 2011); identifying non-overlapping
264
265 ecosystem services (Bateman et al., 2011); modeling spatially-explicit variation in the
266
267 values of ecosystem services (Brander et al., 2012a); and comparing the benefits of
268
269 conservation policies with the costs (Naidoo et al., 2006; Naidoo and Ricketts, 2006;
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271 Murdoch et al., 2007; Balmford et al., 2011). The methodological framework is
272
273 represented in Figure 1. The specific methodologies used to operationalize this
274
275 assessment framework are described in the following sections.
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279 [Figure 1 here]
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2.2 Scenario development

The cost-benefit analysis of MPA expansion involves contrasting counterfactual scenarios that differ solely in terms of the extent and location of MPAs. The analysis undertaken in this study develops six alternative scenarios for MPA expansion that are assessed relative to a baseline scenario of no additional expansion of MPAs. Under the baseline scenario, the current location and extent of MPAs is held constant, representing no further expansion of MPA coverage. The baseline scenario also describes the future values of key parameters in the analysis following current trends, threats and pressures. These parameters include population, income, land based pollution, sedimentation, infrastructure development, climate change and ocean acidification. Regarding the baseline impacts of climate change and other stressors on marine ecosystems, we make use of the spatially explicit threat levels modelled in the Reefs at Risk Revisited study (Burke et al., 2011). These parameters change over the time horizon of the analysis (2015-2050) but are held constant across all scenarios, i.e. the analysis is focused on changes in MPA coverage only. Endogenous effects of MPA expansion on these parameters are not modelled.

The alternative scenarios for MPA expansion are developed along two dimensions. The first dimension describes the proportion of marine area designated as no-take MPA. Following the Aichi and Durban Targets, two alternative extents of areal coverage are assessed: 10% and 30% of total marine area within each national exclusive economic zone (EEZ) and area beyond national jurisdiction (ABNJ). These area targets were selected to loosely correspond with those of the CBD Aichi Target 11 and the upper limit of the Durban Action Plan. It is not the intention, however, that the scenarios model all aspects of the CBD or Durban targets. The second dimension

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362
363 describes the location of MPAs, which is determined by targeting areas with varying
364 levels of marine biodiversity (Kaschner et al. 2013; Aquamaps, 2015) and exposure to
365 human impacts (Halpern et al., 2008). In targeting locations that are characterised by
366 high biodiversity and high human impact, the MPAs serve to mitigate damage: the
367 “Protect to Mitigate” (P2M) scenario. Alternatively, targeting areas with high
368 biodiversity and low human impact provides protection to intact ecosystems from
369 potential future human impact: the “Protect to Preserve” (P2P) scenario. Targeting
370 areas with low biodiversity and low human impact identifies locations that are
371 currently not exploited and do not have biological resources that may be exploited in
372 the future: the “Easy to Expand” (E2E) scenario. These three variants of target location
373 are combined with the two targets for areal extent to give six mapped scenarios.
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388 The location and size of new MPAs are determined by creating allocation priority maps
389 for each of three combinations of target location (high biodiversity and high human
390 impact; high biodiversity and low human impact; low biodiversity and low human
391 impact). The allocation priority maps are combined with the two targets for areal
392 extent (10% and 30% of marine area) to map six scenarios. The spatial allocation of
393 MPAs is further defined to ensure that each key habitat and jurisdiction achieves the
394 same proportional coverage by MPAs. The jurisdictions of Exclusive Economic Zones
395 (EEZs) and Areas Beyond National Jurisdiction (ABNJ) are sub-divided per FAO fishing
396 area.
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408 Existing MPAs (UNEP-WCMC, 2014) are retained in the scenario maps. If a country
409 currently meets the targeted coverage of MPA as a proportion of its EEZ, no
410 reallocation of MPAs takes place and existing MPAs remain in place across all
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421 scenarios. Due to issues of data quality, no areas beyond 70 degrees North or South
422 are included in the analysis.
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428 **2.3 Quantification of bio-physical impacts, costs and benefits**

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430 Quantitative relationships on: 1. bio-physical impacts of MPAs on the marine
431 environment; 2. associated change in the provision of ecosystem services; 3. economic
432 value of marine ecosystem services; and 4. establishment, operating and opportunity
433 costs of MPAs were obtained through extensive literature reviews and, where
434 available, meta-analyses of the relevant literature. Meta-analysis is a method of
435 synthesizing the results of multiple studies that examine the same phenomenon,
436 through the identification of a common effect, which is then 'explained' using
437 regression techniques in a meta-regression model (Stanley, 2001). In addition to
438 identifying consensus in results across studies, we use meta-analysis as a means of
439 transferring parameter values from studied sites to new MPA 'policy sites'. The
440 parameters and models used to quantify MPA costs and benefits are explained
441 separately in the following sections.
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457 **2.4 Cost estimation**

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459 Two broad categories of cost associated with the creation and management of MPAs
460 are included in the analysis: those that are incurred by the implementing agency in
461 establishing and operating the MPA, and those that are incurred by industry and
462 coastal communities in the form of compliance and opportunity costs (the value of
463 foregone activities that are restricted by the MPA). MPA establishment costs include
464 all costs incurred up to and including the designation of the MPA and the initiation of
465 its management, whereas all costs incurred subsequently are classified as recurrent
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483 operating costs (McCrea-Strub et al., 2011). Studies that have examined MPA
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485 establishment costs indicate that these costs are spatially heterogeneous at a fine
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487 scale (Richardson et al., 2006).
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490 The methodology used to estimate the establishment and operating costs of
491
492 expanded MPA coverage takes the following steps:
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- 494
495 1. Literature review to obtain existing cost functions that relate MPA cost to the
496
497 characteristics of the MPA. The cost functions for establishment (McCrea-Strub
498
499 et al., 2011) and operating costs (Balmford et al., 2004) both describe negative
500
501 empirical relationships between cost per unit area and the total area of an
502
503 MPA, suggesting that there are economies of scale in increasing the size of
504
505 MPA. These cost functions are reproduced in the Appendix. It is noted that
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507 these cost functions are based on relatively limited and old data. Moreover,
508
509 the costs of establishing and operating MPAs depend also on other factors (e.g.
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511 distance to nearest port; labour costs; institutional experience of MPAs) but
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513 quantified relationships are currently unavailable. New technological
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515 developments, particularly regarding the monitoring of activities in MPAs,
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517 could bring down costs over time (McCauley et al., 2016).
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- 520
521 2. Taking the mapped scenarios for MPA expansion as a starting point, GIS
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523 analysis is used to produce databases of MPAs under each scenario containing
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525 information on the total area of each MPA.
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- 528
529 3. The costs of establishing and operating each MPA under each expansion
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531 scenario is estimated by combining the data generated in step 2 with the cost
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533 functions obtained in step 1. The estimated costs are adjusted from the price
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543 levels used in the underlying cost functions (2005 price levels for establishment
544 costs; 2000 price levels for operating costs) to the common price level used in
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546 the present analysis (2020) using GDP deflators from the World Bank World
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548 Development Indicators. Note that costs are estimated at the level of
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550 individual, geographically separate MPAs. This scale of analysis allows the
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552 estimated costs to reflect the size distribution of MPAs within each scenario.
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554 We assume that establishment costs are incurred over the period 2015-2020
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556 in equal annual instalments; and that operating costs are incurred in each year
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558 over the period 2020-2050.
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565 The calculation of the opportunity cost of MPA designation to commercial fisheries
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567 involves multiple steps that gather several data sources:
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- 570 1. Estimates of ex-vessel fish prices from Melnychuk et al (2016) are combined
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572 with FAO capture data (FAO, 2012) to estimate the value of marine fisheries at
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574 country level.
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576
- 577 2. The total value of fisheries is then divided by the global ocean area to get an
578
579 average value of fisheries production per km².
580
581
- 582 3. The total area of existing MPAs is subtracted from the estimated total MPA
583
584 area for each of the scenarios being evaluated. This gives the change in MPA
585
586 area (km²) under each MPA scenario.
587
588
- 589 4. The change in MPA area and value per km² are combined to estimate the value
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591 of reduced fisheries production under each scenario. We make the assumption
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593 that the value of fishing production is reduced in proportion to increased MPA
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603 area in the absence of generalised evidence on the scale of displacement. This
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605 is a conservative assumption to avoid underestimating the opportunity cost of
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608 MPAs to fisheries.
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FAO data indicate that global fisheries production peaked and has subsequently plateaued since the mid-1990s. It is assumed in each of the scenarios that the new MPAs are no-take areas. Evidence on spill over effects from MPAs is mixed and likely to be highly context dependent across species, spatial and temporal scales, and the response of the fishing sectors (see Brander et al., 2015). Consequently, our baseline scenario is that fisheries capture remains constant and that the designation of MPAs will result in a reduction in capture pro-rated to the area of each MPA (i.e. no spill overs and no displacement). The base year is 2015 with MPA designation taking full effect from 2020, the present value of fisheries production is then calculated out to 2050 at a discount rate of 3%.

In a sensitivity analysis we relax the assumptions that current capture fisheries production is sustainable and that MPAs have no positive spill over effects. We estimate the opportunity costs to fisheries under the alternative assumption that fisheries production declines over time (at varying annual rates between 1-8%) in combination with the assumption that MPA spill over effects reduce the overall rate of fisheries decline. This reduction in the rate of decline is higher for the 30% MPA scenarios (80% reduction in annual decline) compared to the 10% MPA scenarios (50% reduction in annual decline). We recognise that our approach is highly generalised, however, although our MPA scenarios are spatially explicit we do not have matching spatial data on fisheries effort or catch.

2.5 Benefit estimation

The economic benefits of expanding MPA coverage are the maintained or enhanced flows of ecosystem services that are provided by protected marine ecosystems (Sala et al., 2013; Potts et al., 2014; Pascal et al., 2018). The marine ecosystems included in our assessment are coral reefs, coastal wetlands and mangroves. The marine ecosystem services assessed are the provision of food and other materials for subsistence or commercial use; tourism and recreation; coastal protection; biodiversity; and carbon sequestration.

Spatial data for coral reefs, coastal wetlands and mangroves are obtained from global maps (Burke et al., 2011; Lehner and Döll, 2004; Giri et al., 2011). Differences in ecosystem extent between a baseline scenario, representing spatially variable continuing trends of ecosystem loss, and each MPA expansion scenario are modelled using estimates on MPA effectiveness obtained from the literature. Marginal values for changes in ecosystem extent are subsequently estimated using value functions for coral reef, wetland and mangrove ecosystem services that have been estimated through meta-analyses of the relevant economic valuation literature (Hussain et al., 2011; Brander et al., 2012b). The method used to estimate the change in value of marine ecosystem services following expansion of MPA coverage takes the following steps:

1. Meta-analytic value functions for coral reefs (Hussain et al., 2011), coastal wetlands (Hussain et al., 2011) and mangroves (Brander et al., 2012b) are obtained from the literature and reproduced in the Appendix. The primary

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722
723 valuation data underlying these meta-analyses contain value estimates for a
724
725 variety of ecosystem services. We make use of the benefit functions to
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727 estimate the value of an 'average bundle' of ecosystem services from each
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729 ecosystem rather than a value for each specific service since we have no
730
731 feasible means of modelling the provision and use of specific services at
732
733 specific locations. All three value functions include variables that measure the
734
735 size of the ecosystem and the area of other similar ecosystems in the vicinity.
736
737 These variables are important for capturing the effects of returns to scale at
738
739 the level of individual ecosystems and regionally (Brander et al., 2012a). The
740
741 explanatory power of the value functions is not high and we examine this
742
743 uncertainty in a sensitivity analysis presented in the Appendix together with
744
745 an overview of sources of uncertainty in conducting meta-analytic value
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747 transfers.
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- 752
753 2. GIS processing is used to develop global databases of coral reefs, coastal
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755 wetlands and mangroves containing information on: 1. The extent to which
756
757 each ecosystem parcel is covered by MPA under each scenario; 2. Baseline
758
759 variables including population, income, climate change and other stressors; 3.
760
761 The variables included in the respective value functions obtained in step 1.
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764
765 Global spatial data on coral reefs (n = 56,049) were obtained from the Reefs at
766
767 Risk Revisited project (Burke et al., 2011); coastal wetlands (n = 6,002) were
768
769 extracted from the Global Lakes and Wetlands Database Level 3 (Lehner and
770
771 Döll, 2004); mangroves (n = 124,051) were obtained from US Geological Survey
772
773 data (Giri et al., 2011). The shapefiles for ecosystems were intersected with the
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783 MPA scenario shapefiles, to determine whether individual sites are covered by
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785 an MPA. For mangroves and coastal wetlands, approximately 10% of the total
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787 number of sites are protected. For coral reefs, between 20 and 50% of sites
788
789 are protected depending on the protection scenario.
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792
793 Raster data with projections for composite marine stressor levels (including
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795 climate change, ocean acidification and land based pollution) were obtained
796
797 from the Reefs at Risk Revisited project (Burke et al., 2011).
798
799

800
801 The underlying data used as variables in the value functions include rasters
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803 with population density (CIESIN, 2005); net primary production and human
804
805 appropriation of net primary production (Haberl et al., 2007); and roads
806
807 (Natural Earth, 2015). Regarding the ecosystem abundance variables in the
808
809 value functions, a 50 km radius was drawn around ecosystem site centroids to
810
811 extract the areas of similar ecosystems in the vicinity of each ecosystem site.
812
813

- 814
815 3. Baseline change in the spatial extent of each marine ecosystem is computed
816
817 using estimates of future rates of loss obtained from the literature. For coral
818
819 reefs the baseline rates of loss of coral cover are on average 2% per year and
820
821 distributed around this value to reflect spatial variation in risk (Bruno and Selig,
822
823 2007). For coastal wetlands, baseline rates of loss are 1.5% per year (Lehner
824
825 and Döll, 2004). For mangroves, baseline rates of loss are distributed within
826
827 the range 0.7-3% per year (Pendleton et al., 2012) reflecting spatial variation
828
829 in risk (Burke et al., 2011). Baseline national level GDP and population growth
830
831 rates are obtained from the OECD (OECD, 2012; 2014). Spatially variable rates
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843 of road infrastructure development are obtained from the IMAGE-GLOBIO
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845 model (Alkemade et al., 2009).
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- 847
848 4. Computation of the difference in spatial extent of each ecosystem between
849
850 the baseline and MPA expansion scenarios, i.e. the additional area that would
851
852 not exist under the baseline. The effects of MPA coverage on the spatial extent
853
854 of ecosystems relative to non-protection are obtained from the literature
855
856 review of bio-physical affects of MPAs. For coral reefs, the impact of protection
857
858 is assumed to be a 20% increase in coral cover relative to the baseline
859
860 (Magdaong et al., 2014). For coastal wetlands and mangroves, the annual rate
861
862 of loss is assumed to fall to zero under protection (Murray et al., 2011).
863
864
865
866 5. The value of changes in marine ecosystem services under each MPA expansion
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868 scenario relative to the baseline scenario is estimated by combining the data
869
870 generated in steps 2-4 in the value functions obtained in step 1. The estimated
871
872 benefits are adjusted from the price level used in the underlying meta-analyses
873
874 (2007) to the common price level used in the present analysis (2020) using GDP
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876 deflators from the World Bank World Development Indicators. Note that the
877
878 scale at which this analysis is conducted is at the level of individual,
879
880 geographically distinct, marine ecosystem sites or patches (e.g. individual coral
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882 reefs, wetlands or mangrove forests). This scale of analysis allows the
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884 estimation of values that are specific to the characteristics and context of each
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886 individual marine ecosystem.
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893 The value of avoided carbon emissions and additional sequestration by mangroves
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895 due to expansion of MPA coverage is estimated using methods and parameters
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903 described in the literature (Murray et al., 2011; Pendleton et al., 2012), taking the
904
905 follow steps continuing from step 4 above:
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- 907
908 1. Computation of additional carbon sequestration under each scenario relative
909
910 to the baseline by multiplying the cumulative avoided loss of mangrove area
911
912 by the carbon sequestration rate per unit area: 6.3 tCO₂/ha/year (Pendleton et
913
914 al., 2012).
915
916
- 917
918 2. Computation of avoided release of carbon stored in biomass and substrate by
919
920 multiplying the avoided loss of mangrove area by the rate of carbon release.
921
922 The rate at which stored carbon is released following ecosystem loss is
923
924 different for biomass and substrate carbon and depends on the extent of
925
926 disturbance to substrate. For mangroves, we follow the assumption that 75%
927
928 of biomass carbon is released immediately and that the remaining 25% decays
929
930 with a half-life of 15 years (i.e. a further 12.5% is released within 15 years, a
931
932 further 6.25% is released within 15 years after that, etc.) (Murray et al., 2011).
933
934 We further assume that mangrove soil organic carbon has a half-life of 7.5
935
936 years (i.e. 50% of the stored carbon is released in the first 7.5 years, 25% in the
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938 following 7.5 years, etc.).
939
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- 941
942 3. Computation of total additional carbon stored in each year of the analysis (i.e.
943
944 sum estimates from steps 1 and 2 for each year).
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- 947
948 4. Computation of the value of additional carbon stored in each year of the
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950 analysis by multiplying the estimated total quantity (from step 3) by the value
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952 per tonne CO₂ for each year. The relevant value per tonne of CO₂ is the social
953
954 cost of carbon (SCC), which is the monetary value of damages caused by
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963 emitting one more tonne of CO₂ in a given year (Pearce, 2003). The SCC
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965 therefore also represents the value of damages avoided for a small reduction
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967 in emissions, in other words, the benefit of a reduction in atmospheric CO₂ in
968
969 a given year. The SCC increases over time due to the increasing marginal
970
971 damage caused by additional tonnes of CO₂ in the atmosphere. In our analysis
972
973 we use the US Interagency Working Group series of SCC estimates for the
974
975 period 2010-2050 (Interagency Working Group, 2013).
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979 **2.6 Cost-Benefit Analysis**

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981 Cost benefit analysis (CBA) is a method in which the societal costs and benefits of
982
983 alternative options or scenarios are expressed and compared in monetary terms
984
985 (Hanley and Spash, 1993). CBA provides an indication of how much a prospective
986
987 investment contributes to social welfare by calculating the extent to which the
988
989 benefits of the project exceed the costs. The methodology for the CBA takes the
990
991 following steps:
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995

- 996 1. Quantification of negative and positive effects (costs and benefits) of
997
998 expanding MPAs in monetary units. This gives a time-series of future values for
999
1000 each cost and benefit over the time horizon of the analysis. The time horizon
1001
1002 is the period over which effects are assessed. The time horizon of our analysis
1003
1004 is 2015-2050, which provides a sufficiently long period over which the benefits
1005
1006 of MPAs can be realised.
1007
1008
- 1009 2. Conversion of costs and benefits that are expressed in the price levels of
1010
1011 different years to a common price level. We use GDP deflators from the World
1012
1013 Bank World Development Indicators to convert all values to 2020 price levels.
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3. Conversion of future values of costs and benefits to present values (2015) reflecting society's time preference. This involves discounting the value of costs and benefits that occur in future years. In this analysis we use a discount rate of 3%, which is in line with similar global assessments. In the Supplementary Information we provide a sensitivity analysis of the results to alternative discount rates (1, 3, 5 and 10%).
 4. Compute total present values across each cost and benefit category by summing each time-series of costs and benefits.
 5. Compute total present value costs and benefits by summing across all costs categories and benefit categories.
 6. Compute the net present value (NPV) of each scenario by subtracting the sum of present value costs from the sum of present value benefits. A positive NPV indicates that the scenario represents an improvement social welfare.
 7. Compute the benefit cost ratio (BCR) of each exploratory scenario as the sum of discounted benefits and the sum of discounted costs. The BCR indicates the proportionate extent to which benefits exceed costs under each scenario. A BCR greater than 1 indicates that the benefits of a scenario exceed the costs.

2.7 Sensitivity analysis

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The cost benefit analysis of MPA expansion is characterised by uncertainties from multiple sources, including the data, functional relationships and parameter values that are used to define MPA locations and quantify costs and benefits. We conduct a sensitivity analysis to explore the robustness of the results to variations in key

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1082
1083 parameter values and assumptions. The CBA results are re-calculated using upper and
1084
1085 lower bound estimates for each category of cost and benefit to examine whether the
1086
1087 conclusions of the analysis are robust to plausible variations in parameter values.
1088

- 1089
1090 1. Lower and upper bound costs and benefits are calculated as 95% prediction
1091
1092 intervals. Prediction intervals for values estimated using cost or value
1093
1094 functions are computed using the method proposed by Osborne (2000) and
1095
1096 provide an indication of the precision with which the meta-analytic functions
1097
1098 can predict out-of-sample values.
1099
- 1100
1101 2. For costs and benefits that are estimated using methods other than function
1102
1103 value transfer (i.e. opportunity costs to fisheries and mangrove carbon
1104
1105 benefits), lower and upper bounds are computed using the method proposed
1106
1107 by Pendleton et al. (2012). This approach involves an assumed range of
1108
1109 variation around a central estimate based on values obtained from the
1110
1111 literature. For mangrove carbon, we follow Pendleton et al. (2012) and
1112
1113 examine variations in parameter values that are 37.5% lower and higher than
1114
1115 central values. For opportunity costs to fisheries we use the distribution of
1116
1117 outcomes from alternative assumptions on rates of fisheries decline and spill
1118
1119 over effects.
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- 1122
1123 3. NPV and BCR of each scenario is re-calculated using alternative combinations
1124
1125 of lower and upper bound values for each cost and benefit.
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1129 A separate analysis is conducted of the sensitivity of the CBA results to the choice of
1130
1131 discount rate used to compute present value costs and benefits. The BCR for each
1132
1133 scenario is re-calculated using alternative discount rates of 0, 1, 3, 5 and 10%.
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1143 All data and code used in the analysis (MPA expansion scenarios; GIS analysis;
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1145 estimation of costs, benefits, net present values, benefit-cost ratios; and sensitivity
1146
1147 analysis) are available from the authors on request.
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1152 **3. Results**

1153 **3.1. Scenarios for expansion of Marine Protected Areas**

1154
1155 The location of extant MPAs and the spatial allocation of MPAs under each of the six
1156
1157 expansion scenarios are represented in Figure 2. Existing MPAs are not reallocated
1158
1159 and so EEZs with current high protection, such as Australia, show limited difference
1160
1161 across scenarios. The protect-to-mitigate allocation creates groups of MPAs along the
1162
1163 coast in each EEZ, with no protection in the remaining EEZ. Protection is taken up
1164
1165 again in ABNJs at the EEZ boundary, resulting in corridors of non-protection. In the
1166
1167 protect-to-preserve scenario, MPAs are distributed within EEZs to protect key habitats
1168
1169 but tend to be further away from shore to avoid high human activity. The easy-to-
1170
1171 expand scenario allocates large MPAs to the centre of open oceans just North and
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1173 South of the inter-tropical convergence zone (ITCZ) and in some cases to remote
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1175 coasts.
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1181 [Figure 2 here]
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1188 **3.2. Costs of expanding Marine Protected Areas**

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1190 The total MPA establishment costs for each scenario are reported in Table 1 and range
1191
1192 between US\$ 11 billion under P2M-10% and US\$ 14 billion under P2P-30%. The costs
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1194 of establishing MPAs increase with the extent of MPA coverage but not at a linear
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1203 rate. There are substantial economies of scale, i.e. the cost per unit area decreases as
1204
1205 the area of an MPA increases. The P2P-30% scenario has higher establishment costs
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1207 than the other scenarios due to the size distribution of MPAs under this scenario, in
1208
1209 which there is a greater number of small, relatively high cost, MPAs in comparison to
1210
1211 other scenarios.
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1214
1215 The total MPA operating costs for each scenario are reported in Table 1 and range
1216
1217 between US\$ 40 billion under P2M-10% and US\$ 44 billion under P2P-30%. These
1218
1219 costs also display substantial economies of scale, due to the agglomeration of many
1220
1221 smaller and relatively more costly MPAs into fewer and larger MPAs. We note that the
1222
1223 future costs of monitoring MPAs are expected to decline further with the
1224
1225 development of new technologies, such as automatic ship identification systems (AIS)
1226
1227 (McCauley et al., 2016).
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1230
1231 The estimated opportunity costs to fisheries are reported in Table 1 and range
1232
1233 between US\$ 257 billion under E2E-10% and US\$ 777 billion under P2P-30%. The
1234
1235 opportunity costs to fisheries are an order of magnitude higher than establishment
1236
1237 and management costs.
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1241 [Figure 3 here]
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1244 1245 **3.3. Benefits of expanding Marine Protected Areas** 1246

1247 The aggregated present values of benefits of improved provision of marine ecosystem
1248
1249 services for each scenario are presented in Table 1 and range between US\$ 692 billion
1250
1251 under E2E-10% and US\$ 1,274 billion under P2P-30%. The estimated benefits of MPA
1252
1253 protection are substantial, reflecting both the high economic value of marine
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1255 ecosystem services and the high rates of loss in the absence of additional protection
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1262
1263 under the baseline. The results also show very large differences in the yield of benefits
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1265 across scenarios. The spatial distribution of MPAs under the P2P scenario, i.e.
1266
1267 targeting areas with high biodiversity and low human impact, delivers considerably
1268
1269 higher benefits.
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1271
1272 The value of avoided carbon emissions and additional sequestration by mangroves
1273
1274 that are protected by MPAs is reported separately from other mangrove ecosystem
1275
1276 service values in Table 2. The value of additional stored carbon represents a
1277
1278 substantial proportion of the benefits obtained by protecting mangroves
1279
1280 (approximately 40% of mangrove benefits), although this is only a small proportion of
1281
1282 total benefits across all assessed ecosystems (4.5%).
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1286
1287 [Figure 4 here]
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1290 **3.4. Cost-Benefit Analysis of expanding Marine Protected Areas**

1291
1292 The results of the cost-benefit analysis of MPA expansion are presented in Table 1 and
1293
1294 represented in Figure 5. Under all scenarios, the expansion of MPAs has a positive
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1296 benefit-cost ratio, in the range 1.4 – 2.7. In the case of the P2P-10% scenario, targeting
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1298 areas with high biodiversity and low human impact with up to 10% coverage of total
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1300 marine area, each dollar invested yields a return of just under 3 dollars-worth of
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1302 benefits. The net improvement in human well-being, as measured by the net present
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1304 value (NPV) of each scenario, is estimated to be in the range USD 223-644 billion over
1305
1306 the period 2015–2050. On this evidence, investing in MPAs is economically advisable.
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1309
1310 The results show that there are substantial differences between the scenarios,
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1312 indicating that the scale of expansion and targeted locations of MPAs makes a
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1314 considerable difference to their economic performance. The E2E-10% scenario,
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1323 targeting low biodiversity and low human impact areas with up to 10% coverage of
1324 total marine area, has the lowest costs (and in that sense lives up to its epithet “Easy-
1325 to-Expand”) but also yields the lowest benefits. Creating MPAs to simply meet the
1326 spatial requirements of the Aichi and Durban Targets at lowest cost will result in
1327 positive net returns but would miss the opportunity to obtain higher benefits from
1328 marine ecosystem services. Pursuing an expansion of MPA coverage that targets areas
1329 of high biodiversity yields substantially higher returns.
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1339 The results also reveal the presence of diminishing returns to scale from expanding
1340 MPAs. Under the P2M and P2P scenarios, expanding MPAs from 10% to 30% coverage
1341 of total marine area results in a less than proportionate increase in net benefits;
1342 whereas under the E2E scenario, the net benefit of 30% coverage is actually lower
1343 than for 10% coverage. This also reflected by the lower benefit-cost ratios for 30%
1344 coverage, as compared to the corresponding 10% coverage scenarios. The underlying
1345 reason for diminishing returns to scale in this analysis is that the marine habitats that
1346 deliver the highest benefits are already protected under the 10% cover scenarios. The
1347 marginal establishment and operating costs of MPAs decline with scale but these cost
1348 categories constitute a relatively small share of total costs.
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1365 [Table 1 here]

1366 [Figure 5 here]

1367 [Figure 6 here]

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1383 **3.5. Sensitivity analysis**
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1385 Lower and upper bound values for each cost and benefit category are reported in
1386 Table 1. Both the costs and benefits of MPA expansion are highly uncertain, reflecting
1387 the current limitations of our understanding of the costs of expanding MPAs, how
1388 MPAs impact the provision of ecosystem services, and the magnitude of the benefits
1389 of those services. Nevertheless, estimates for each cost and benefit category do not
1390 vary from central value estimates by more than a factor 3.
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1399 To assess the robustness of the central CBA result given this level of uncertainty in
1400 input values, we re-calculate the NPV and BCR of each scenario using alternative
1401 combinations of lower and upper bound values for each cost and benefit. The results
1402 are presented in Tables 2 and 3 for NPVs and BCRs respectively. For all scenarios the
1403 NPV remains positive and the BCR remains greater than 1 except in the extreme case
1404 of lower bound benefits and upper bound costs, indicating that the economic
1405 feasibility of MPA expansion is robust to plausible variation in costs and benefits. Even
1406 in the extreme case that all benefits are at the lower bound and all costs at the upper
1407 bound, the E2E10 and P2P10 scenarios remain economically viable.
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1419 [Table 2 here]
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1421 [Table 3 here]
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1424 The sensitivity analysis of CBA results to the choice of discount rate is reported in Table
1425 4. As expected, using a higher discount rate has the effect of decreasing the BCRs. This
1426 is due to the temporal distributions of costs and benefits, with the costs of MPAs being
1427 predominantly incurred in the near term and (increasing) benefits accruing in the long
1428 term. Increasing the discount rate therefore places a lower weight on future benefits
1429 relative to the more immediate costs of MPA expansion. The overall outcome of the
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1443 CBA is not sensitive to the discount rate and only with a discount rate of 10%, the BCR
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1445 for E2E10, P2P10 and P2P30 fall below 1.
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1447
1448 [Table 4 here]
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1450 1451 **4. Discussion**

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1453 The analysis of the costs and benefits of MPA expansion is characterised by
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1455 uncertainties from multiple sources. The following caveats and limitations provide a
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1457 descriptive assessment of the main uncertainties in the analysis.
1458

1459
1460 The scale of the analysis is global and necessarily involves large generalisations. The
1461
1462 globally aggregated results provide an indication of the economic performance of
1463
1464 each scenario as a whole. The analysis is therefore not suited to determine costs and
1465
1466 benefits at the national level, particularly given the limited representation of
1467
1468 temperate ecosystems on the benefit side. At the national level, and to a greater
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1470 extent at the level of individual MPAs, there is likely to be much wider variation in net
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1472 benefits, including the possibility of negative returns.
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1476
1477 The scenarios for MPA expansion are defined by a small set of simple rules in order to
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1479 explore broad alternative strategies for MPA expansion. The spatial allocation of MPAs
1480
1481 under each scenario does not therefore reflect the wide range factors that would
1482
1483 ideally be considered in the actual siting and design of MPAs. In particular, the siting
1484
1485 of MPAs, and subsequent assessment of costs and benefits, does not account for
1486
1487 network or connectivity effects (Pujolar et al., 2013) or for institutional factors of MPA
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1489 expansion (Mora et al., 2009). Future analyses could explore the possibility of applying
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1491 a dynamic optimisation approach to maximise the net benefits from MPAs in each EEZ
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1502
1503 and ABNJ, which could potentially allow MPA coverage to exceed current targets in
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1505 some jurisdictions or fall short in others.
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1507
1508 The analysis is incomplete in terms of its coverage of the full range of costs and
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1510 benefits. On the cost side, we are unable to quantify and value all opportunity costs
1511
1512 resulting from MPA expansion. These include costs to shipping; oil, gas and mineral
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1514 extraction; off-shore wind power generation; and subsistence fishing. It is also
1515
1516 possible that some tourism and recreation activities will be restricted. Shipping costs
1517
1518 are not expected to be greatly affected by MPA expansion because MPAs may
1519
1520 continue to allow shipping and route distance is only a partial determinant of total
1521
1522 shipping costs (Martínez-Zarzoso and Nowak-Lehmann, 2007). Regarding subsistence
1523
1524 fisheries, the associated values, where available, are generally comparable to those of
1525
1526 commercial fisheries. These values do not, however, fully reflect the potential impact
1527
1528 of MPA designation on livelihoods, loss of traditional lifestyles and social
1529
1530 consequences. There may also be positive spillovers for subsistence fisheries due to
1531
1532 the removal of commercial fishing pressure. Although we note this impact, it is not
1533
1534 possible to quantify it in the current analysis.
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1540 The analysis also does not take account of potential displacement effects of protected
1541
1542 areas. Restricting human activities within MPAs may, to some extent, lead to the
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1544 displacement of those activities to unprotected areas, which can experience greater
1545
1546 degradation and loss of ecosystem services as a result. A greater degree of fishing
1547
1548 effort displacement would mean that the estimated opportunity costs to fisheries are
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1550 over estimated. Displaced fishing effort, however, would likely involve higher costs,
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1552 which would reduce the net returns and increase the opportunity costs to fisheries.
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1562
1563 Similarly, if the restricted supply of fish due to MPA expansion results in higher prices,
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1565 this might off-set losses to commercial fisheries to some extent and reduce the
1566
1567 opportunity costs of MPA designation. These complex second and third order effects
1568
1569 require further analysis.
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1571
1572
1573 On the benefit side, we are unable to quantify impacts to all marine ecosystems (e.g.
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1575 pelagic, seamounts, seagrass, kelp forests) and all ecosystem services (e.g. existence
1576
1577 values associated with marine biodiversity) that are potentially positively impacted by
1578
1579 MPAs. The marine ecosystems for which we are able to model the benefits of MPA
1580
1581 coverage are predominantly coastal and tropical (i.e. coral reefs, mangroves and
1582
1583 coastal wetlands) and it has proved harder to model the effects of MPAs on open
1584
1585 ocean and temperate ecosystems. Polar regions are omitted from the analysis due to
1586
1587 issues of data quality underlying the scenario maps.
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1590
1591 The analysis therefore only provides a partial assessment of all costs and benefits and
1592
1593 should be revisited as the necessary data and knowledge become available. On
1594
1595 balance, we expect that the most important categories of costs and benefits are
1596
1597 included in our analysis and that adding further information would tend to increase
1598
1599 the benefits of expansion relative to costs, particularly due the high values that people
1600
1601 place on the continued existence of marine biodiversity (McVittie and Moran, 2010;
1602
1603 Börger et al., 2014; Jobsvogt et al., 2014; Brouwer et al., 2016). The measurement of
1604
1605 such values is challenging but they are likely to constitute an important benefit of
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1607 protection.
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1612 Our analysis focuses on how the economic value of marine ecosystem services to
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1614 people and communities is expected to change with the expansion of Marine
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1622
1623 Protected Areas. It is recognised, however, that instrumental economic value derived
1624
1625 from ecosystem services is only one component of the overall value of the marine
1626
1627 environment (Turner, 1999) and that the intrinsic value of nature also provides an
1628
1629 argument for the conservation of the marine habitats and biodiversity (Balmford et al.
1630
1631 2011).
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1633

1634 **5. Conclusions**

1635
1636 The results of this study indicate that the global expansion of MPA coverage, as aimed
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1638 for by the Aichi and Durban Targets, can be recommended from an economic
1639
1640 perspective. Depending on the proportion and the location of marine area designated
1641
1642 as no-take MPA, the benefits exceed the costs by between 1.4–2.7 times. The
1643
1644 comparison of spatially diverse scenarios for expansion reveals that targeting
1645
1646 protection towards pristine areas with high biodiversity yields higher returns than
1647
1648 focusing on areas with low biodiversity or areas that have experienced high human
1649
1650 impact.
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1652

1653
1654 The results are conditional on the strong assumption that all MPAs are effectively
1655
1656 managed and enforced. A large proportion of existing MPAs, however, are not
1657
1658 effectively enforced or managed (Mora et al., 2009; Gill et al., 2017), which represents
1659
1660 a missed investment opportunity. There is a need for increased management
1661
1662 effectiveness and enforcement of MPAs, in addition to their expansion, in order to
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1664 realize the positive returns identified by this study.
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1670 The positive benefit-cost ratios at the global scale should not be taken to necessarily
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1672 imply that all individual MPAs are economically viable. Careful work is required to
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1674 consider the circumstances of each proposed MPA, and the social, economic and
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1683 environmental conditions prevailing in each case (Hargreaves-Allen et al., 2011). In
1684
1685 many cases it may be possible to tailor the degree of protection to obtain the benefits
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1687 without necessarily restricting all activities. In addition, it is important to recognise
1688
1689 that the costs and benefits associated with an MPA will not be evenly distributed
1690
1691 across stakeholder groups (Gurney et al., 2014). These concerns need to be addressed
1692
1693 directly in the design of MPAs together with possible compensation for stakeholders
1694
1695 that face net costs. Such compensation might also be warranted at a transboundary
1696
1697 scale, from countries that are net-beneficiaries to countries that incur net costs. In
1698
1699 developing new MPAs, full use should be made of existing knowledge and resources
1700
1701 for designing effective MPAs (Salm et al., 2000; Roberts et al., 2003; Mora et al., 2006;
1702
1703 McCloud et al., 2008; OECD, 2017; Brander, 2018).

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1708 The impacts of climate change and ocean acidification on marine ecosystems are
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1710 expected to increase markedly after 2050 (Dupont and Pörtner, 2013), which is
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1712 beyond the time horizon of our analysis. The benefits of more action now to protect
1713
1714 and build ecosystem resilience in the face of future climate change and ocean
1715
1716 acidification will therefore only be realized in the long term. These long-term benefits
1717
1718 provide a further argument for current expansion of MPAs.

1719
1720
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1762
1763 authors declare no competing financial interests.
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1766
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1768
1769 mapped the scenarios for MPA expansion and prepared Figure 2; F.E. conducted the
1770
1771 additional GIS analysis; L.A.C.v.d.L conducted the review of biophysical impacts; C.B.
1772
1773 conducted the review of ecosystem service impacts; A.M. estimated the opportunity
1774
1775 costs to fisheries; L.M.B estimated the MPA establishment and operating costs,
1776
1777 ecosystem service benefits and conducted the cost-benefit analysis; all authors
1778
1779 contributed to analyses and interpretation; L.M.B. drafted the manuscript.
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Appendix: Cost and benefit functions used in the analysis

Table A1. MPA establishment cost function. Source: McCrea-Strub et al. (2011).

Variable	Units	Coefficient	P
Establishment cost	2005 USD/km ² ; log ₁₀		
Intercept		4.66	
MPA area	km ² ; log ₁₀	-0.48	<0.001
N		13	
F		35.1	

Table A2. MPA operating cost function. Source: Balmford et al. (2004).

Variable	Units	Coefficient	Std. Error
Operating cost	2000 USD/km ² /year; log ₁₀		
Intercept		5.02	
MPA area	km ² ; log ₁₀	-0.80	17.2
N		80	
R ²		0.79	

Table A3. Coral reef value function. Source: Hussain et al. (2011)

Variable	Units ¹	Coefficient	Std. Error
Value of ecosystem services (dependent)	USD/ha/year; 2007; ln		
Intercept		16.093	3.707
Area of coral cover	ha; ln	-0.293	0.066
GDP per capita	2007 USD; ln	0.039	0.099
Population within 50 km	population; ln	0.238	0.154
Area of coral reef within 50 km	ha; ln	-0.207	0.107
Length of roads within 50 km	km; ln	-0.035	0.054
Net primary production within 50 km	tonnes; ln	-0.379	0.287
Human appropriation of net primary production within 50km	tonnes; ln	-0.076	0.231
N		163	
Adjusted R ²		0.18	

¹ ln denotes natural logarithm

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Table A4. Wetland value function. Source: Hussain et al. (2011).

Variable	Units ¹	Coefficient	Std. Error
Value of ecosystem services (dependent)	USD/ha/year; 2007; ln		
Intercept		1.708	1.978
Area of wetland	ha; ln	-0.209	0.049
GDP per capita (PPP US\$ 2007)	2007 USD; ln	0.610	0.106
Area of lakes and rivers within 50 km	ha; ln	0.159	0.081
Area of wetlands within 50 km	ha; ln	-0.175	0.048
Population within 50 km	population; ln	0.426	0.106
Human appropriation of NPP within 50 km	tonnes; ln	-0.201	0.118
N		247	
Adjusted R ²		0.32	

¹ ln denotes natural logarithm

Table A5. Mangrove value function. Source: Brander et al. (2012a)

Variable	Units ¹	Coefficient	Std. Error
Value of ecosystem services (dependent)	USD/ha/year; 2007; ln		
Intercept		-0.590	3.157
Dummy variable for coastal protection ES		1.456	0.069
Dummy variable for water quality ES		1.714	0.218
Dummy variable for fisheries ES		0.860	0.194
Dummy variable for fuel wood ES		-1.085	0.083
Area of mangrove	ha; ln	-0.343	0.173
Area of mangroves within 50 km	km ² ; ln	0.248	0.182
Length of roads within 50 km	km; ln	-0.312	0.064
GDP per capita (USD; ln)	2007 USD; ln	0.785	3.157
Population within 50 km	population; ln	0.284	0.069
N		111	
Adjusted R ²		0.41	

¹ ln denotes natural logarithm

Figure 1. Methodological framework for assessing the net benefits of expanding Marine Protected Areas.

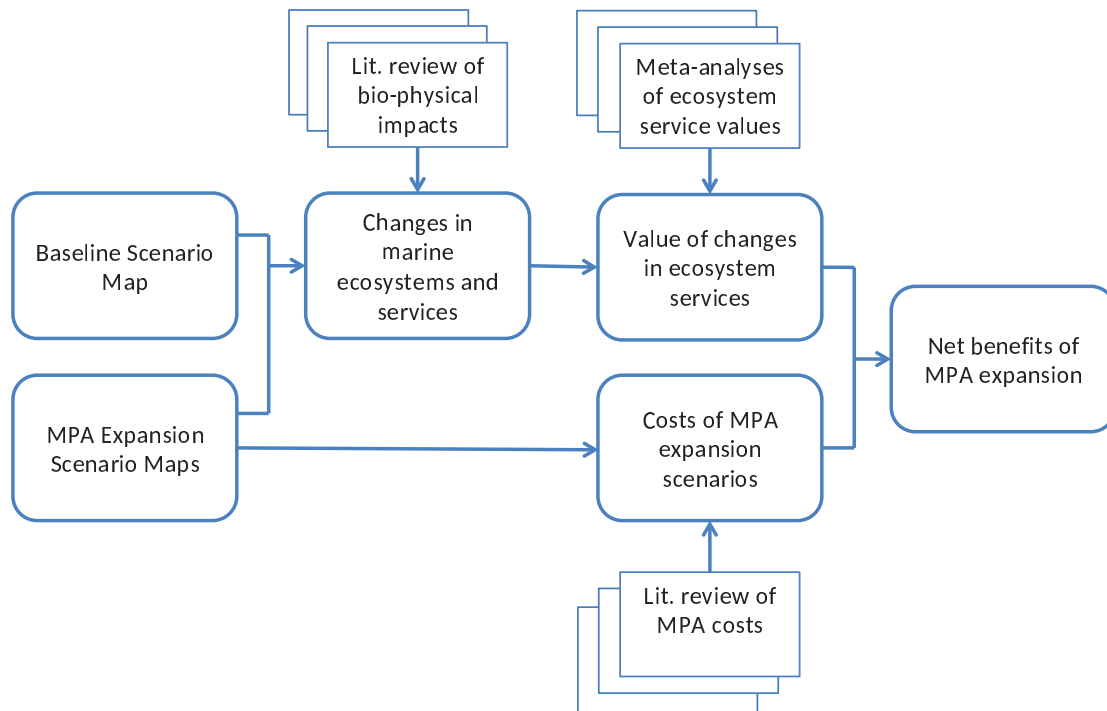
Figure 2. Current and future global distributions of Marine Protected Areas. Scenario acronyms: P2P "Protect to Preserve", P2M "Protect to Mitigate", E2E "Easy to Expand".

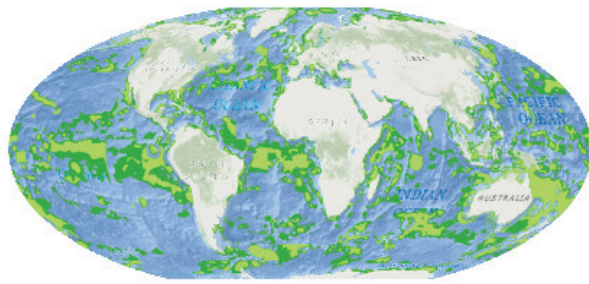
Figure 3. Costs of expanding MPAs (US\$; billions; 2020 price level; present values over the period 2015-2030 using a discount rate of 3%). Error bars represent 95% confidence intervals. Acronyms: P2P "Protect to Preserve", P2M "Protect to Mitigate", E2E "Easy to Expand".

Figure 4. Benefits of expanding MPAs (US\$; billions; 2020 price level; present values over the period 2015-2030 using a discount rate of 3%). Error bars represent 95% confidence intervals. Scenario acronyms: P2P "Protect to Preserve", P2M "Protect to Mitigate", E2E "Easy to Expand".

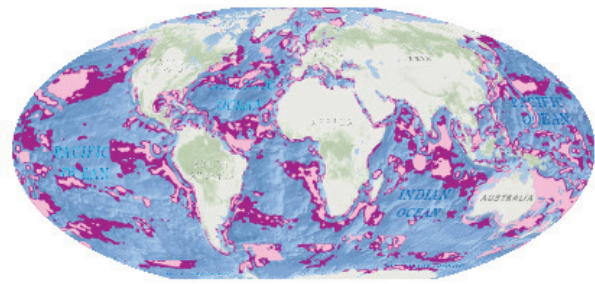
Figure 5. Net present values (US\$; billions; 2020 price level; discount rate 3%). Error bars represent the combinations of high benefits-low costs (upper bound) and low benefits-high costs (lower bound) drawn from 95% prediction intervals for each cost and benefit. Scenario acronyms: P2P "Protect to Preserve", P2M "Protect to Mitigate", E2E "Easy to Expand".

Figure 6. Benefit cost ratios (discount rate 3%). Error bars represent the combinations of high benefits-low costs (upper bound) and low benefits-high costs (lower bound) drawn from 95% prediction intervals for each cost and benefit. Scenario acronyms: P2P "Protect to Preserve", P2M "Protect to Mitigate", E2E "Easy to Expand".

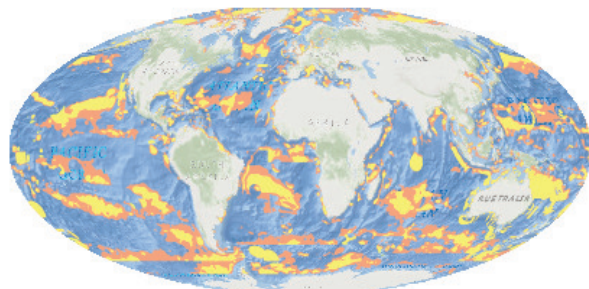




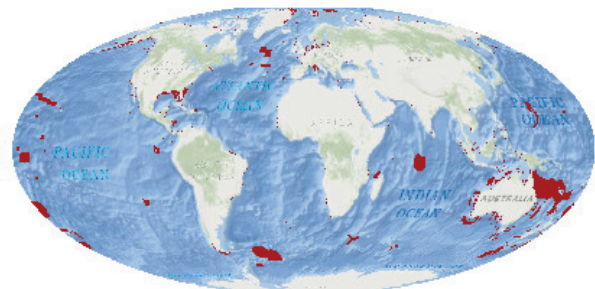
P2P



P2M



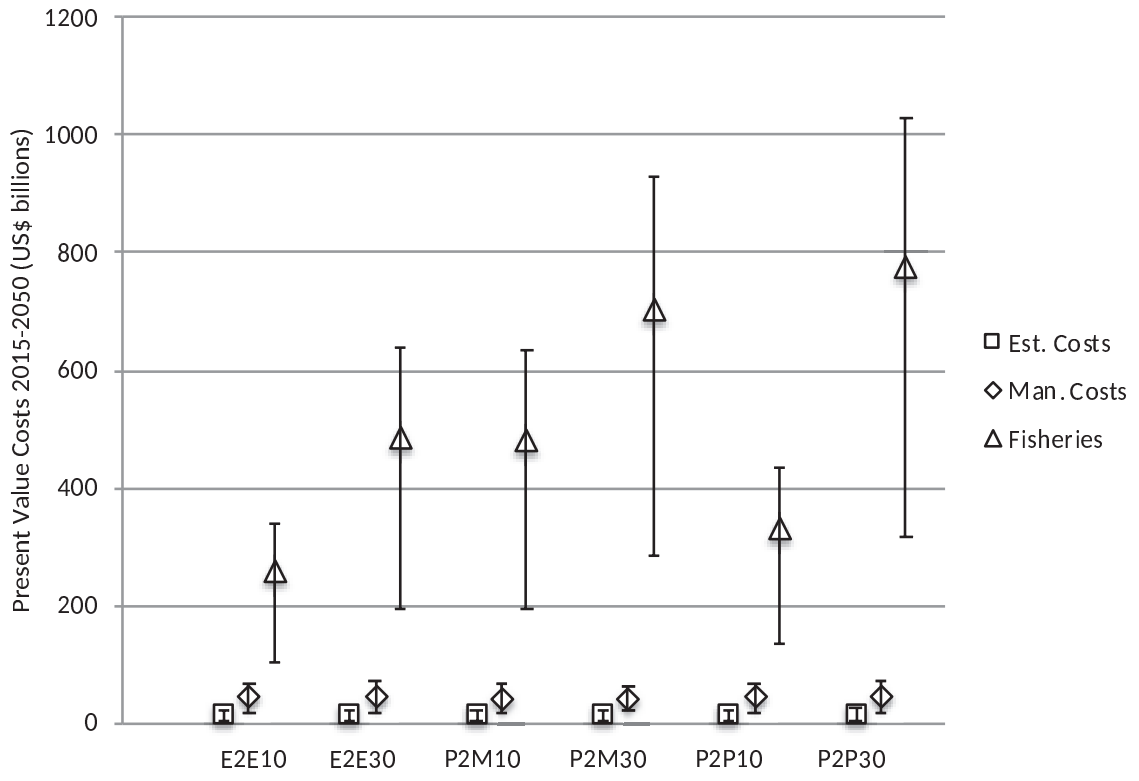
E2E

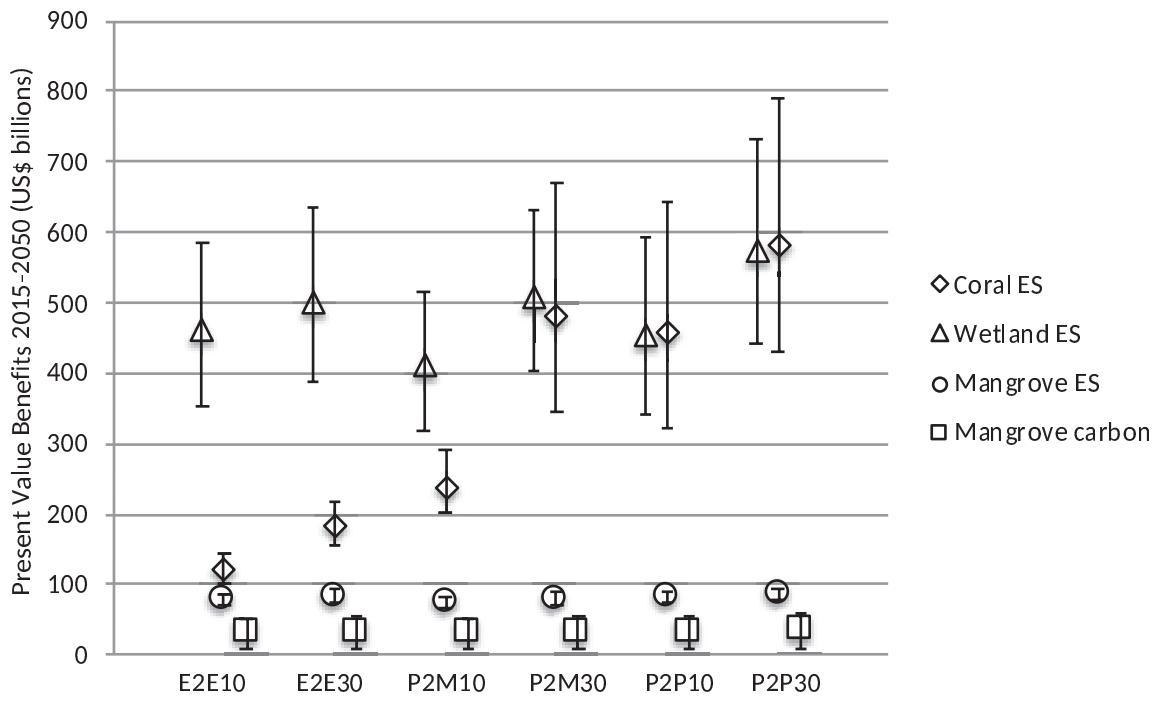


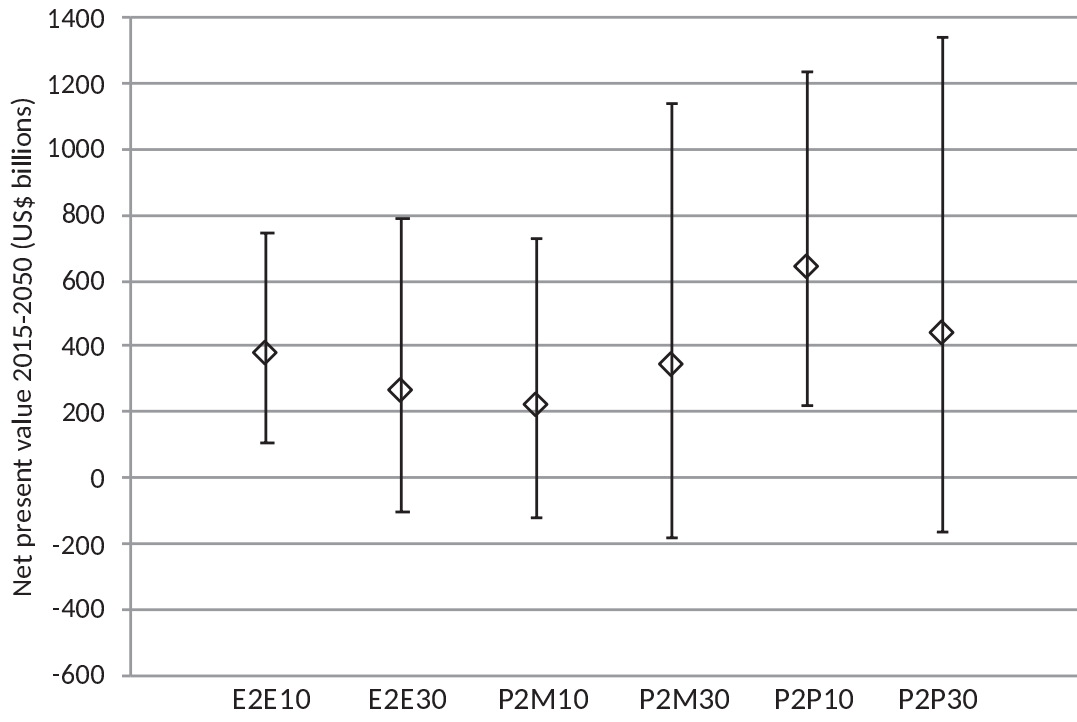
Current MPAs

P2P - 10% Expansion
 P2M - 10% Expansion
 E2E - 10% Expansion
 Current Marine Protected Areas

P2P - 30% Expansion
 P2M - 30% Expansion
 E2E - 30% Expansion







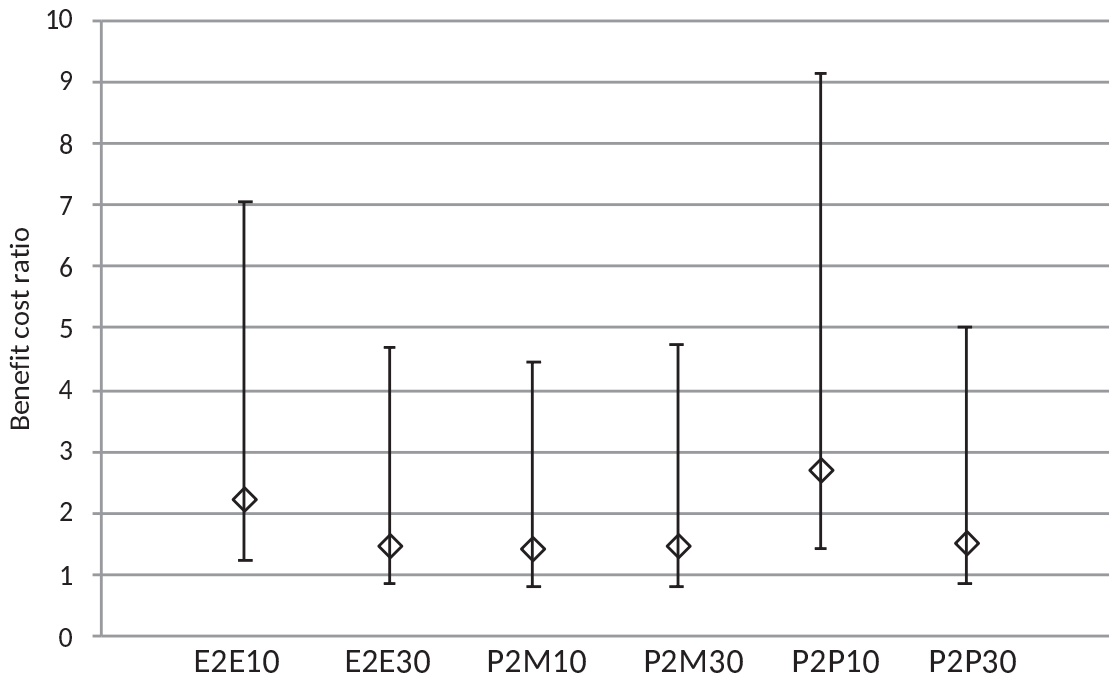


Table 1. Cost-Benefit Analysis of expanding MPAs (US\$; billions; 2020 price level; present values over the period 2015-2050 using a discount rate of 3%). 95% prediction intervals in parentheses. Scenario acronyms: P2P “Protect to Preserve”, P2M “Protect to Mitigate”, E2E “Easy to Expand”.

	E2E10	E2E30	P2M10	P2M30	P2P10	P2P30
Operating Costs	43 (17-68)	44 (16-72)	40 (15-65)	41 (19-64)	42 (16-67)	44 (17-71)
Establishment Costs	12 (2-21)	12 (2-22)	11 (2-20)	12 (2-21)	12 (2-21)	14 (2-25)
Fisheries Costs	257 (104-340)	482 (195-638)	479 (194-634)	701 (283-928)	329 (133-436)	777 (314-1029)
Total Costs	311 (123-429)	538 (213-732)	530 (211-719)	754 (304-1013)	382 (151-524)	835 (333-1125)
Coral Benefits	121 (103-146)	183 (156-217)	238 (202-289)	480 (346-671)	457 (322-644)	580 (431-789)
Mangrove Benefits	78 (71-86)	84 (76-92)	75 (68-83)	80 (72-89)	83 (76-92)	87 (79-95)
Mangrove carbon	31 (7-53)	33 (8-56)	30 (7-51)	32 (9-54)	33 (8-56)	34 (8-58)
Wetland ES	462 (355-585)	501 (387-634)	409 (320-514)	507 (402-631)	453 (340-592)	574 (440-731)
Total Benefits	692 (536-869)	800 (626-1,000)	753 (598-937)	1100 (829-1,444)	1027 (745-1,383)	1274 (957-1,673)
Net Present Value	381	262	223	345	644	439
Benefit-Cost Ratio	2.2	1.5	1.4	1.5	2.7	1.5

Table 2. Net present values for combinations of lower and upper bound cost and benefit estimates (US\$; billions; 2020 price level; present values using a discount rate of 3%). Scenario acronyms: P2P “Protect to Preserve”, P2M “Protect to Mitigate”, E2E “Easy to Expand”.

	E2E10	E2E30	P2M10	P2M30	P2P10	P2P30
Central Benefit; Central Cost	381	262	223	345	644	439
Low Benefit; Low Cost	413	413	387	525	594	624
High Benefit; Low Cost	746	787	726	1140	1232	1340
Low Benefit; High Cost	107	-107	-121	-184	221	-168
High Benefit; High Cost	440	267	218	431	859	548

Table 3. Benefit-Cost Ratios for combinations of lower and upper bound cost and benefit estimates.

Acronyms: P2P “Protect to Preserve”, P2M “Protect to Mitigate”, E2E “Easy to Expand”.

	E2E10	E2E30	P2M10	P2M30	P2P10	P2P30
Central Benefit; Central Cost	2.2	1.5	1.4	1.5	2.7	1.5
Low Benefit; Low Cost	4.3	2.9	2.8	2.7	4.9	2.9
High Benefit; Low Cost	7.0	4.7	4.4	4.7	9.2	5.0
Low Benefit; High Cost	1.2	0.9	0.8	0.8	1.4	0.9
High Benefit; High Cost	2.0	1.4	1.3	1.4	2.6	1.5

Table 4. Sensitivity of Benefit-Cost Ratios to alternative discount rates. Scenario acronyms: P2P “Protect to Preserve”, P2M “Protect to Mitigate”, E2E “Easy to Expand”.

Discount rate	E2E10	E2E30	P2M10	P2M30	P2P10	P2P30
0%	2.7	1.8	1.7	1.8	3.3	1.8
1%	2.5	1.7	1.6	1.7	3.1	1.7
3%	2.2	1.5	1.4	1.5	2.7	1.5
5%	1.9	1.3	1.2	1.3	2.3	1.3
10%	1.4	0.9	0.9	0.9	1.7	1.0

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