The global costs and benefits of expanding Marine Protected Areas

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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

1. Introduction

In response to increasing degradation of the marine environment and declining provision of ecosystem services, several national and international initiatives have called for the development of Marine Protected Areas (MPAs) (CBD, 2010). An MPA is a clearly defined geographical space, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values (IUCN, 2008). MPAs can improve the condition of marine ecosystems through diverse ecological pathways and, although challenging to quantify (Fox et al. 2014), result in improved biological parameters such as habitat complexity, survival rates of juvenile fish, species diversity, fish biomass, density and size (Lester et al., 2009). Improved ecosystem condition may translate into improved provision of ecosystem services, particularly in terms of tourism and recreation (Badalamenti et al., 2000; Potts et al. 2014), fisheries in adjacent areas through spill over effects (Roberts et al., 2001; Gell and Roberts, 2003) and cultural values associated with the conservation of marine biodiversity and mega-fauna (Cañadas et al., 2005).

Currently, 4.8% of global marine area is designated as MPA, with approximately 2.2% established as no-take MPAs (Atlas of Marine Protection, 2019). The location of existing MPAs is represented in Figure 2. The two predominant statements calling for the global expansion of networks of MPAs are the Convention on Biological Diversity (CBD) Aichi Target 11 and the Durban Action Plan developed at the 2003 Vth IUCN World Parks Congress, which call for an expansion of MPA coverage to 10% and 30% of global marine area respectively.

Progress towards meeting the Aichi and Durban Targets has been made but considerably more investment is required to ensure the effectiveness and ecological representativeness of MPAs, in addition to their geographic coverage (Dunn et al, 2014; Fox et al., 2014; Edgar et al., 2014, Boonzaier and Pauly, 2016; Gill et al., 2017). Moreover, political support for meeting the Durban and Aichi Targets might be increased by providing better information about the societal and economic relevance of MPAs. MPAs may be viewed by some decision makers primarily as ecological reserves rather than as assets that generate multiple services such as food, coastal protection, carbon sequestration, genetic material and recreational opportunities (Beaumont et al., 2007; Böhnke-Henricks et al., 2013). These services have high economic values in terms of their contribution to specific sectors of the economy such as fisheries and tourism and also as non-marketed constituents of human well-being (Costanza et al., 1997; de Groot et al., 2012).

The contribution of this study is to estimate the global costs and benefits of increasing no-take MPA coverage to evaluate the economic case for expanding MPAs. Earlier studies have examined the financial costs of establishing and operating MPAs (Balmford et al., 2004; McCrea-Strub et al., 2011), and the benefits of closing the high seas to fishing (White and Costello, 2014), but this study is the first to compare the economic costs and benefits of MPA expansion worldwide. On the cost side, the assessment includes the costs of establishing and operating MPAs, and the opportunity costs to commercial fisheries. On the benefit side, the marine ecosystems included in the assessment are coral reefs, coastal wetlands and mangroves; and 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. This framing and assessment of the costs and benefits of expanding MPAs is intended to inform and motivate on-going discussions on global coverage and placement of MPAs, including the development of a new strategy for the Convention on Biological Diversity for the period 2021-2030.

This assessment of the global costs and benefits of MPA expansion applies value transfer methods (Johnston et al., 2015) in which information from existing studies on MPA costs and ecosystem service values are transferred and scaled up across marine areas that are protected by additional (hypothetical) MPAs under alternative future scenarios. Using value transfer methods is arguably the only viable means of estimating ecosystem service values at a global scale (Brander et al., 2012a; Costanza et al., 2014) but this approach is characterised by several limitations and potential inaccuracies (Rosenberger and Stanley, 2006). A potentially important source of inaccuracy is so-called 'generalisation error', which occurs when values for study sites are transferred to policy sites that are different without fully accounting for those differences (Rosenberger and Phipps, 2007). The present study applies a multi-disciplinary approach to explicitly account for spatial heterogeneity in ecological and economic conditions in the estimation of MPA costs and benefits.

The structure of the remainder of the paper is as follows: Section 2 describes the methods applied in the analysis, including the overall methodological framework, scenario development, cost estimation, benefit estimation, cost-benefit analysis, and sensitivity analysis; Section 3 present the results in the form of mapped scenarios for MPA expansion, monetary values of costs and benefits for each scenario, output statistics for the cost-benefit analysis, and a sensitivity analysis of the results to variation in key parameters; Section 4 discusses the main results, uncertainties and limitations of the analysis; and Section 5 provides conclusions.

2. Methods

2.1 Methodological framework

The methodological framework for the analysis combines data, methods and insights from multiple disciplines including marine geography, biology, management and economics. The framework broadly follows the ecosystem services approach (Kumar, 2012) and incorporates several critical insights from the environmental economics literature by: contrasting counterfactual scenarios that differ solely in whether they include policy interventions (Hussain et al., 2011); identifying non-overlapping ecosystem services (Bateman et al., 2011); modeling spatially-explicit variation in the values of ecosystem services (Brander et al., 2012a); and comparing the benefits of conservation policies with the costs (Naidoo et al., 2006; Naidoo and Ricketts, 2006; Murdoch et al., 2007; Balmford et al., 2011). The methodological framework is represented in Figure 1. The specific methodologies used to operationalize this assessment framework are described in the following sections.

[Figure 1 here]

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 describes the location of MPAs, which is determined by targeting areas with varying levels of marine biodiversity (Kaschner et al. 2013; Aquamaps, 2015) and exposure to human impacts (Halpern et al., 2008). In targeting locations that are characterised by high biodiversity and high human impact, the MPAs serve to mitigate damage: the “Protect to Mitigate” (P2M) scenario. Alternatively, targeting areas with high biodiversity and low human impact provides protection to intact ecosystems from potential future human impact: the “Protect to Preserve” (P2P) scenario. Targeting areas with low biodiversity and low human impact identifies locations that are currently not exploited and do not have biological resources that may be exploited in the future: the “Easy to Expand” (E2E) scenario. These three variants of target location are combined with the two targets for areal extent to give six mapped scenarios.

The location and size of new MPAs are determined by creating allocation priority maps for each of three combinations of target location (high biodiversity and high human impact; high biodiversity and low human impact; low biodiversity and low human impact). The allocation priority maps are combined with the two targets for areal extent (10% and 30% of marine area) to map six scenarios. The spatial allocation of MPAs is further defined to ensure that each key habitat and jurisdiction achieves the same proportional coverage by MPAs. The jurisdictions of Exclusive Economic Zones (EEZs) and Areas Beyond National Jurisdiction (ABNJ) are sub-divided per FAO fishing area.

Existing MPAs (UNEP-WCMC, 2014) are retained in the scenario maps. If a country currently meets the targeted coverage of MPA as a proportion of its EEZ, no reallocation of MPAs takes place and existing MPAs remain in place across all scenarios. Due to issues of data quality, no areas beyond 70 degrees North or South are included in the analysis.

2.3 Quantification of bio-physical impacts, costs and benefits

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

2.4 Cost estimation

Two broad categories of cost associated with the creation and management of MPAs are included in the analysis: those that are incurred by the implementing agency in establishing and operating the MPA, and those that are incurred by industry and coastal communities in the form of compliance and opportunity costs (the value of foregone activities that are restricted by the MPA). MPA establishment costs include all costs incurred up to and including the designation of the MPA and the initiation of its management, whereas all costs incurred subsequently are classified as recurrent operating costs (McCrea-Strub et al., 2011). Studies that have examined MPA establishment costs indicate that these costs are spatially heterogeneous at a fine scale (Richardson et al., 2006).

The methodology used to estimate the establishment and operating costs of expanded MPA coverage takes the following steps:

1. Literature review to obtain existing cost functions that relate MPA cost to the characteristics of the MPA. The cost functions for establishment (McCrea-Strub et al., 2011) and operating costs (Balmford et al., 2004) both describe negative empirical relationships between cost per unit area and the total area of an MPA, suggesting that there are economies of scale in increasing the size of MPA. These cost functions are reproduced in the Appendix. It is noted that these cost functions are based on relatively limited and old data. Moreover, the costs of establishing and operating MPAs depend also on other factors (e.g. distance to nearest port; labour costs; institutional experience of MPAs) but quantified relationships are currently unavailable. New technological developments, particularly regarding the monitoring of activities in MPAs, could bring down costs over time (McCauley et al., 2016).

2. Taking the mapped scenarios for MPA expansion as a starting point, GIS analysis is used to produce databases of MPAs under each scenario containing information on the total area of each MPA.

3. The costs of establishing and operating each MPA under each expansion scenario is estimated by combining the data generated in step 2 with the cost functions obtained in step 1. The estimated costs are adjusted from the price

levels used in the underlying cost functions (2005 price levels for establishment costs; 2000 price levels for operating costs) to the common price level used in the present analysis (2020) using GDP deflators from the World Bank World Development Indicators. Note that costs are estimated at the level of individual, geographically separate MPAs. This scale of analysis allows the estimated costs to reflect the size distribution of MPAs within each scenario. We assume that establishment costs are incurred over the period 2015-2020 in equal annual instalments; and that operating costs are incurred in each year over the period 2020-2050.

The calculation of the opportunity cost of MPA designation to commercial fisheries involves multiple steps that gather several data sources:

1. Estimates of ex-vessel fish prices from Melnychuk et al (2016) are combined with FAO capture data (FAO, 2012) to estimate the value of marine fisheries at country level.
2. The total value of fisheries is then divided by the global ocean area to get an average value of fisheries production per km^2.
3. The total area of existing MPAs is subtracted from the estimated total MPA area for each of the scenarios being evaluated. This gives the change in MPA area (km^2) under each MPA scenario.
4. The change in MPA area and value per km^2 are combined to estimate the value of reduced fisheries production under each scenario. We make the assumption that the value of fishing production is reduced in proportion to increased MPA

area in the absence of generalised evidence on the scale of displacement. This is a conservative assumption to avoid underestimating the opportunity cost of MPAs to fisheries.

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

valuation data underlying these meta-analyses contain value estimates for a variety of ecosystem services. We make use of the benefit functions to estimate the value of an 'average bundle' of ecosystem services from each ecosystem rather than a value for each specific service since we have no feasible means of modelling the provision and use of specific services at specific locations. All three value functions include variables that measure the size of the ecosystem and the area of other similar ecosystems in the vicinity. These variables are important for capturing the effects of returns to scale at the level of individual ecosystems and regionally (Brander et al., 2012a). The explanatory power of the value functions is not high and we examine this uncertainty in a sensitivity analysis presented in the Appendix together with an overview of sources of uncertainty in conducting meta-analytic value transfers.

2. GIS processing is used to develop global databases of coral reefs, coastal wetlands and mangroves containing information on: 1. The extent to which each ecosystem parcel is covered by MPA under each scenario; 2. Baseline variables including population, income, climate change and other stressors; 3. The variables included in the respective value functions obtained in step 1.

   Global spatial data on coral reefs (n = 56,049) were obtained from the Reefs at Risk Revisited project (Burke et al., 2011); coastal wetlands (n = 6,002) were extracted from the Global Lakes and Wetlands Database Level 3 (Lehner and Döll, 2004); mangroves (n = 124,051) were obtained from US Geological Survey data (Giri et al., 2011). The shapefiles for ecosystems were intersected with the

MPA scenario shapefiles, to determine whether individual sites are covered by an MPA. For mangroves and coastal wetlands, approximately 10% of the total number of sites are protected. For coral reefs, between 20 and 50% of sites are protected depending on the protection scenario.

Raster data with projections for composite marine stressor levels (including climate change, ocean acidification and land based pollution) were obtained from the Reefs at Risk Revisited project (Burke et al., 2011).

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

3. Baseline change in the spatial extent of each marine ecosystem is computed using estimates of future rates of loss obtained from the literature. For coral reefs the baseline rates of loss of coral cover are on average 2% per year and distributed around this value to reflect spatial variation in risk (Bruno and Selig, 2007). For coastal wetlands, baseline rates of loss are 1.5% per year (Lehner and Döll, 2004). For mangroves, baseline rates of loss are distributed within the range 0.7-3% per year (Pendleton et al., 2012) reflecting spatial variation in risk (Burke et al., 2011). Baseline national level GDP and population growth rates are obtained from the OECD (OECD, 2012; 2014). Spatially variable rates

of road infrastructure development are obtained from the IMAGE-GLOBIO model (Alkemade et al., 2009).

4. Computation of the difference in spatial extent of each ecosystem between the baseline and MPA expansion scenarios, i.e. the additional area that would not exist under the baseline. The effects of MPA coverage on the spatial extent of ecosystems relative to non-protection are obtained from the literature review of bio-physical affects of MPAs. For coral reefs, the impact of protection is assumed to be a 20% increase in coral cover relative to the baseline (Magdaong et al., 2014). For coastal wetlands and mangroves, the annual rate of loss is assumed to fall to zero under protection (Murray et al., 2011).

5. The value of changes in marine ecosystem services under each MPA expansion scenario relative to the baseline scenario is estimated by combining the data generated in steps 2-4 in the value functions obtained in step 1. The estimated benefits are adjusted from the price level used in the underlying meta-analyses (2007) to the common price level used in the present analysis (2020) using GDP deflators from the World Bank World Development Indicators. Note that the scale at which this analysis is conducted is at the level of individual, geographically distinct, marine ecosystem sites or patches (e.g. individual coral reefs, wetlands or mangrove forests). This scale of analysis allows the estimation of values that are specific to the characteristics and context of each individual marine ecosystem.

The value of avoided carbon emissions and additional sequestration by mangroves due to expansion of MPA coverage is estimated using methods and parameters described in the literature (Murray et al., 2011; Pendleton et al., 2012), taking the follow steps continuing from step 4 above:

1. Computation of additional carbon sequestration under each scenario relative to the baseline by multiplying the cumulative avoided loss of mangrove area by the carbon sequestration rate per unit area: 6.3 tCO_2/ha/year (Pendleton et al., 2012).

2. Computation of avoided release of carbon stored in biomass and substrate by multiplying the avoided loss of mangrove area by the rate of carbon release. The rate at which stored carbon is released following ecosystem loss is different for biomass and substrate carbon and depends on the extent of disturbance to substrate. For mangroves, we follow the assumption that 75% of biomass carbon is released immediately and that the remaining 25% decays with a half-life of 15 years (i.e. a further 12.5% is released within 15 years, a further 6.25% is released within 15 years after that, etc.) (Murray et al., 2011). We further assume that mangrove soil organic carbon has a half-life of 7.5 years (i.e. 50% of the stored carbon is released in the first 7.5 years, 25% in the following 7.5 years, etc.).

3. Computation of total additional carbon stored in each year of the analysis (i.e. sum estimates from steps 1 and 2 for each year).

4. Computation of the value of additional carbon stored in each year of the analysis by multiplying the estimated total quantity (from step 3) by the value per tonne CO_2 for each year. The relevant value per tonne of CO_2 is the social cost of carbon (SCC), which is the monetary value of damages caused by

emitting one more tonne of CO_2 in a given year (Pearce, 2003). The SCC therefore also represents the value of damages avoided for a small reduction in emissions, in other words, the benefit of a reduction in atmospheric CO_2 in a given year. The SCC increases over time due to the increasing marginal damage caused by additional tonnes of CO_2 in the atmosphere. In our analysis we use the US Interagency Working Group series of SCC estimates for the period 2010-2050 (Interagency Working Group, 2013).

2.6 Cost-Benefit Analysis

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

1. Quantification of negative and positive effects (costs and benefits) of expanding MPAs in monetary units. This gives a time-series of future values for each cost and benefit over the time horizon of the analysis. The time horizon is the period over which effects are assessed. The time horizon of our analysis is 2015-2050, which provides a sufficiently long period over which the benefits of MPAs can be realised.

2. Conversion of costs and benefits that are expressed in the price levels of different years to a common price level. We use GDP deflators from the World Bank World Development Indicators to convert all values to 2020 price levels.

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

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

1. Lower and upper bound costs and benefits are calculated as 95% prediction intervals. Prediction intervals for values estimated using cost or value functions are computed using the method proposed by Osborne (2000) and provide an indication of the precision with which the meta-analytic functions can predict out-of-sample values.
2. For costs and benefits that are estimated using methods other than function value transfer (i.e. opportunity costs to fisheries and mangrove carbon benefits), lower and upper bounds are computed using the method proposed by Pendleton et al. (2012). This approach involves an assumed range of variation around a central estimate based on values obtained from the literature. For mangrove carbon, we follow Pendleton et al. (2012) and examine variations in parameter values that are 37.5% lower and higher than central values. For opportunity costs to fisheries we use the distribution of outcomes from alternative assumptions on rates of fisheries decline and spill over effects.
3. NPV and BCR of each scenario is re-calculated using alternative combinations of lower and upper bound values for each cost and benefit.

A separate analysis is conducted of the sensitivity of the CBA results to the choice of discount rate used to compute present value costs and benefits. The BCR for each scenario is re-calculated using alternative discount rates of 0, 1, 3, 5 and 10%.

All data and code used in the analysis (MPA expansion scenarios; GIS analysis; estimation of costs, benefits, net present values, benefit-cost ratios; and sensitivity analysis) are available from the authors on request.

3. Results

3.1. Scenarios for expansion of Marine Protected Areas

The location of extant MPAs and the spatial allocation of MPAs under each of the six expansion scenarios are represented in Figure 2. Existing MPAs are not reallocated and so EEZs with current high protection, such as Australia, show limited difference across scenarios. The protect-to-mitigate allocation creates groups of MPAs along the coast in each EEZ, with no protection in the remaining EEZ. Protection is taken up again in ABNJs at the EEZ boundary, resulting in corridors of non-protection. In the protect-to-preserve scenario, MPAs are distributed within EEZs to protect key habitats but tend to be further away from shore to avoid high human activity. The easy-to-expand scenario allocates large MPAs to the centre of open oceans just North and South of the inter-tropical convergence zone (ITCZ) and in some cases to remote coasts.

[Figure 2 here]

3.2. Costs of expanding Marine Protected Areas

The total MPA establishment costs for each scenario are reported in Table 1 and range between US$ 11 billion under P2M-10% and US$ 14 billion under P2P-30%. The costs of establishing MPAs increase with the extent of MPA coverage but not at a linear rate. There are substantial economies of scale, i.e. the cost per unit area decreases as the area of an MPA increases. The P2P-30% scenario has higher establishment costs than the other scenarios due to the size distribution of MPAs under this scenario, in which there is a greater number of small, relatively high cost, MPAs in comparison to other scenarios.

The total MPA operating costs for each scenario are reported in Table 1 and range between US$ 40 billion under P2M-10% and US$ 44 billion under P2P-30%. These costs also display substantial economies of scale, due to the agglomeration of many smaller and relatively more costly MPAs into fewer and larger MPAs. We note that the future costs of monitoring MPAs are expected to decline further with the development of new technologies, such as automatic ship identification systems (AIS) (McCauley et al., 2016).

The estimated opportunity costs to fisheries are reported in Table 1 and range between US$ 257 billion under E2E-10% and US$ 777 billion under P2P-30%. The opportunity costs to fisheries are an order of magnitude higher than establishment and management costs.

[Figure 3 here]

3.3. Benefits of expanding Marine Protected Areas

The aggregated present values of benefits of improved provision of marine ecosystem services for each scenario are presented in Table 1 and range between US$ 692 billion under E2E-10% and US$ 1,274 billion under P2P-30%. The estimated benefits of MPA protection are substantial, reflecting both the high economic value of marine ecosystem services and the high rates of loss in the absence of additional protection under the baseline. The results also show very large differences in the yield of benefits across scenarios. The spatial distribution of MPAs under the P2P scenario, i.e. targeting areas with high biodiversity and low human impact, delivers considerably higher benefits.

The value of avoided carbon emissions and additional sequestration by mangroves that are protected by MPAs is reported separately from other mangrove ecosystem service values in Table 2. The value of additional stored carbon represents a substantial proportion of the benefits obtained by protecting mangroves (approximately 40% of mangrove benefits), although this is only a small proportion of total benefits across all assessed ecosystems (4.5%).

[Figure 4 here]

3.4. Cost-Benefit Analysis of expanding Marine Protected Areas

The results of the cost-benefit analysis of MPA expansion are presented in Table 1 and represented in Figure 5. Under all scenarios, the expansion of MPAs has a positive benefit-cost ratio, in the range 1.4 – 2.7. In the case of the P2P-10% scenario, targeting areas with high biodiversity and low human impact with up to 10% coverage of total marine area, each dollar invested yields a return of just under 3 dollars-worth of benefits. The net improvement in human well-being, as measured by the net present value (NPV) of each scenario, is estimated to be in the range USD 223-644 billion over the period 2015–2050. On this evidence, investing in MPAs is economically advisable.

The results show that there are substantial differences between the scenarios, indicating that the scale of expansion and targeted locations of MPAs makes a considerable difference to their economic performance. The E2E-10% scenario, targeting low biodiversity and low human impact areas with up to 10% coverage of total marine area, has the lowest costs (and in that sense lives up to its epithet “Easy-to-Expand”) but also yields the lowest benefits. Creating MPAs to simply meet the spatial requirements of the Aichi and Durban Targets at lowest cost will result in positive net returns but would miss the opportunity to obtain higher benefits from marine ecosystem services. Pursuing an expansion of MPA coverage that targets areas of high biodiversity yields substantially higher returns.

The results also reveal the presence of diminishing returns to scale from expanding MPAs. Under the P2M and P2P scenarios, expanding MPAs from 10% to 30% coverage of total marine area results in a less than proportionate increase in net benefits; whereas under the E2E scenario, the net benefit of 30% coverage is actually lower than for 10% coverage. This also reflected by the lower benefit-cost ratios for 30% coverage, as compared to the corresponding 10% coverage scenarios. The underlying reason for diminishing returns to scale in this analysis is that the marine habitats that deliver the highest benefits are already protected under the 10% cover scenarios. The marginal establishment and operating costs of MPAs decline with scale but these cost categories constitute a relatively small share of total costs.

[Table 1 here]

[Figure 5 here]

[Figure 6 here]

3.5. Sensitivity analysis

Lower and upper bound values for each cost and benefit category are reported in Table 1. Both the costs and benefits of MPA expansion are highly uncertain, reflecting the current limitations of our understanding of the costs of expanding MPAs, how MPAs impact the provision of ecosystem services, and the magnitude of the benefits of those services. Nevertheless, estimates for each cost and benefit category do not vary from central value estimates by more than a factor 3.

To assess the robustness of the central CBA result given this level of uncertainty in input values, we re-calculate the NPV and BCR of each scenario using alternative combinations of lower and upper bound values for each cost and benefit. The results are presented in Tables 2 and 3 for NPVs and BCRs respectively. For all scenarios the NPV remains positive and the BCR remains greater than 1 except in the extreme case of lower bound benefits and upper bound costs, indicating that the economic feasibility of MPA expansion is robust to plausible variation in costs and benefits. Even in the extreme case that all benefits are at the lower bound and all costs at the upper bound, the E2E10 and P2P10 scenarios remain economically viable.

[Table 2 here]

[Table 3 here]

The sensitivity analysis of CBA results to the choice of discount rate is reported in Table 4. As expected, using a higher discount rate has the effect of decreasing the BCRs. This is due to the temporal distributions of costs and benefits, with the costs of MPAs being predominantly incurred in the near term and (increasing) benefits accruing in the long term. Increasing the discount rate therefore places a lower weight on future benefits relative to the more immediate costs of MPA expansion. The overall outcome of the

CBA is not sensitive to the discount rate and only with a discount rate of 10%, the BCR for E2E10, P2P10 and P2P30 fall below 1.

[Table 4 here]

4. Discussion

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

The scale of the analysis is global and necessarily involves large generalisations. The globally aggregated results provide an indication of the economic performance of each scenario as a whole. The analysis is therefore not suited to determine costs and benefits at the national level, particularly given the limited representation of temperate ecosystems on the benefit side. At the national level, and to a greater extent at the level of individual MPAs, there is likely to be much wider variation in net benefits, including the possibility of negative returns.

The scenarios for MPA expansion are defined by a small set of simple rules in order to explore broad alternative strategies for MPA expansion. The spatial allocation of MPAs under each scenario does not therefore reflect the wide range factors that would ideally be considered in the actual siting and design of MPAs. In particular, the siting of MPAs, and subsequent assessment of costs and benefits, does not account for network or connectivity effects (Pujolar et al., 2013) or for institutional factors of MPA expansion (Mora et al., 2009). Future analyses could explore the possibility of applying a dynamic optimisation approach to maximise the net benefits from MPAs in each EEZ and ABNJ, which could potentially allow MPA coverage to exceed current targets in some jurisdictions or fall short in others.

The analysis is incomplete in terms of its coverage of the full range of costs and benefits. On the cost side, we are unable to quantify and value all opportunity costs resulting from MPA expansion. These include costs to shipping; oil, gas and mineral extraction; off-shore wind power generation; and subsistence fishing. It is also possible that some tourism and recreation activities will be restricted. Shipping costs are not expected to be greatly affected by MPA expansion because MPAs may continue to allow shipping and route distance is only a partial determinant of total shipping costs (Martínez-Zarzoso and Nowak-Lehmann, 2007). Regarding subsistence fisheries, the associated values, where available, are generally comparable to those of commercial fisheries. These values do not, however, fully reflect the potential impact of MPA designation on livelihoods, loss of traditional lifestyles and social consequences. There may also be positive spillovers for subsistence fisheries due to the removal of commercial fishing pressure. Although we note this impact, it is not possible to quantify it in the current analysis.

The analysis also does not take account of potential displacement effects of protected areas. Restricting human activities within MPAs may, to some extent, lead to the displacement of those activities to unprotected areas, which can experience greater degradation and loss of ecosystem services as a result. A greater degree of fishing effort displacement would mean that the estimated opportunity costs to fisheries are over estimated. Displaced fishing effort, however, would likely involve higher costs, which would reduce the net returns and increase the opportunity costs to fisheries.

Similarly, if the restricted supply of fish due to MPA expansion results in higher prices, this might off-set losses to commercial fisheries to some extent and reduce the opportunity costs of MPA designation. These complex second and third order effects require further analysis.

On the benefit side, we are unable to quantify impacts to all marine ecosystems (e.g. pelagic, seamounts, seagrass, kelp forests) and all ecosystem services (e.g. existence values associated with marine biodiversity) that are potentially positively impacted by MPAs. The marine ecosystems for which we are able to model the benefits of MPA coverage are predominantly coastal and tropical (i.e. coral reefs, mangroves and coastal wetlands) and it has proved harder to model the effects of MPAs on open ocean and temperate ecosystems. Polar regions are omitted from the analysis due to issues of data quality underlying the scenario maps.

The analysis therefore only provides a partial assessment of all costs and benefits and should be revisited as the necessary data and knowledge become available. On balance, we expect that the most important categories of costs and benefits are included in our analysis and that adding further information would tend to increase the benefits of expansion relative to costs, particularly due the high values that people place on the continued existence of marine biodiversity (McVittie and Moran, 2010; Börger et al., 2014; Jobsvogt et al., 2014; Brouwer et al., 2016). The measurement of such values is challenging but they are likely to constitute an important benefit of protection.

Our analysis focuses on how the economic value of marine ecosystem services to people and communities is expected to change with the expansion of Marine

Protected Areas. It is recognised, however, that instrumental economic value derived from ecosystem services is only one component of the overall value of the marine environment (Turner, 1999) and that the intrinsic value of nature also provides an argument for the conservation of the marine habitats and biodiversity (Balmford et al. 2011).

5. Conclusions

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

The results are conditional on the strong assumption that all MPAs are effectively managed and enforced. A large proportion of existing MPAs, however, are not effectively enforced or managed (Mora et al., 2009; Gill et al., 2017), which represents a missed investment opportunity. There is a need for increased management effectiveness and enforcement of MPAs, in addition to their expansion, in order to realize the positive returns identified by this study.

The positive benefit-cost ratios at the global scale should not be taken to necessarily imply that all individual MPAs are economically viable. Careful work is required to consider the circumstances of each proposed MPA, and the social, economic and environmental conditions prevailing in each case (Hargreaves-Allen et al., 2011). In many cases it may be possible to tailor the degree of protection to obtain the benefits without necessarily restricting all activities. In addition, it is important to recognise that the costs and benefits associated with an MPA will not be evenly distributed across stakeholder groups (Gurney et al., 2014). These concerns need to be addressed directly in the design of MPAs together with possible compensation for stakeholders that face net costs. Such compensation might also be warranted at a transboundary scale, from countries that are net-beneficiaries to countries that incur net costs. In developing new MPAs, full use should be made of existing knowledge and resources for designing effective MPAs (Salm et al., 2000; Roberts et al., 2003; Mora et al., 2006; McCloud et al., 2008; OECD, 2017; Brander, 2018).

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

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Author Contributions: L.M.B. and P.v.B co-led the research; L.N. developed and mapped the scenarios for MPA expansion and prepared Figure 2; F.E. conducted the additional GIS analysis; L.A.C.v.d.L conducted the review of biophysical impacts; C.B. conducted the review of ecosystem service impacts; A.M. estimated the opportunity costs to fisheries; L.M.B estimated the MPA establishment and operating costs, ecosystem service benefits and conducted the cost-benefit analysis; all authors 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

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.

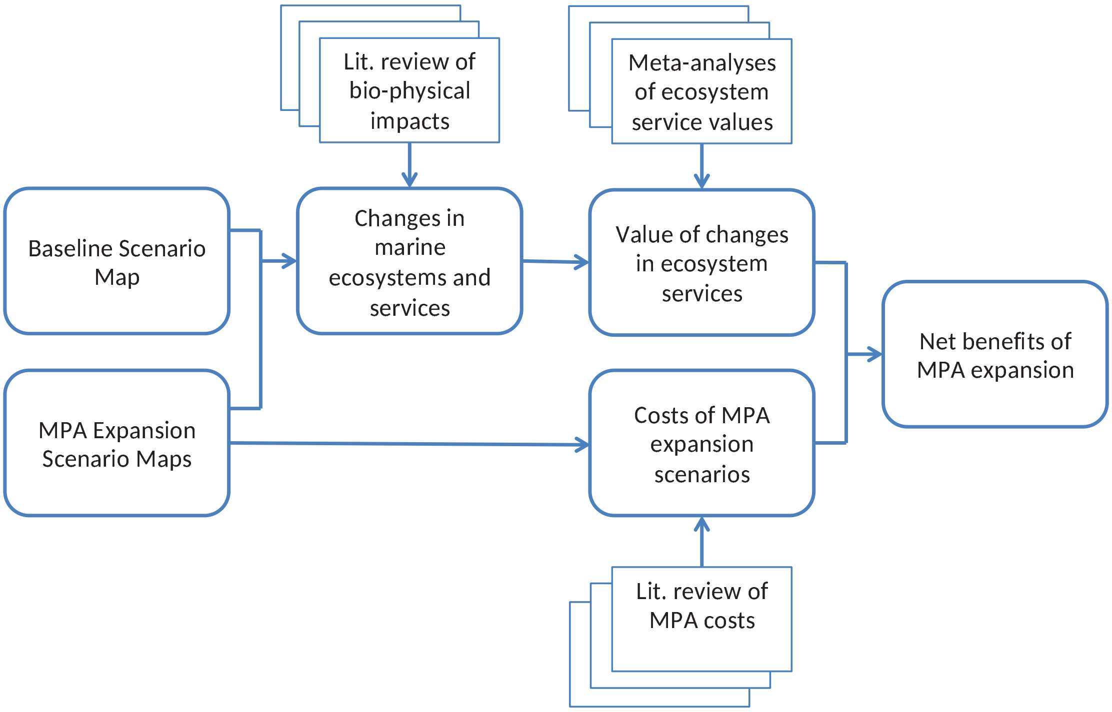
Figure 2. Current and future global distributions of Marine Protected Areas. Scenario acronyms: P2P "Protect to Preserve", P2M "Protect to Mitigate", E2E "Easy to Expand".

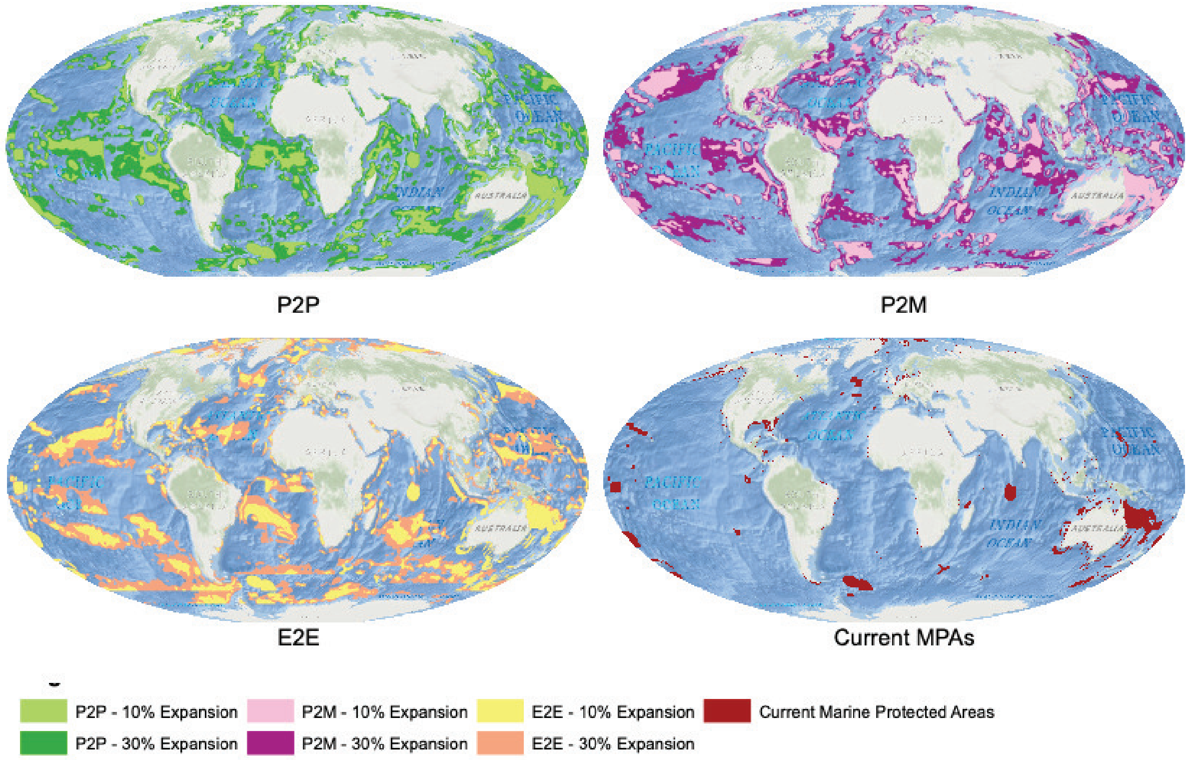
Figure 3. Costs of expanding MPAs (US$; billions; 2020 price level; present values over the period 2015-2030 using a discount rate of 3%). Error bars represent 95% confidence intervals. Acronyms: P2P "Protect to Preserve", P2M "Protect to Mitigate", E2E "Easy to Expand".

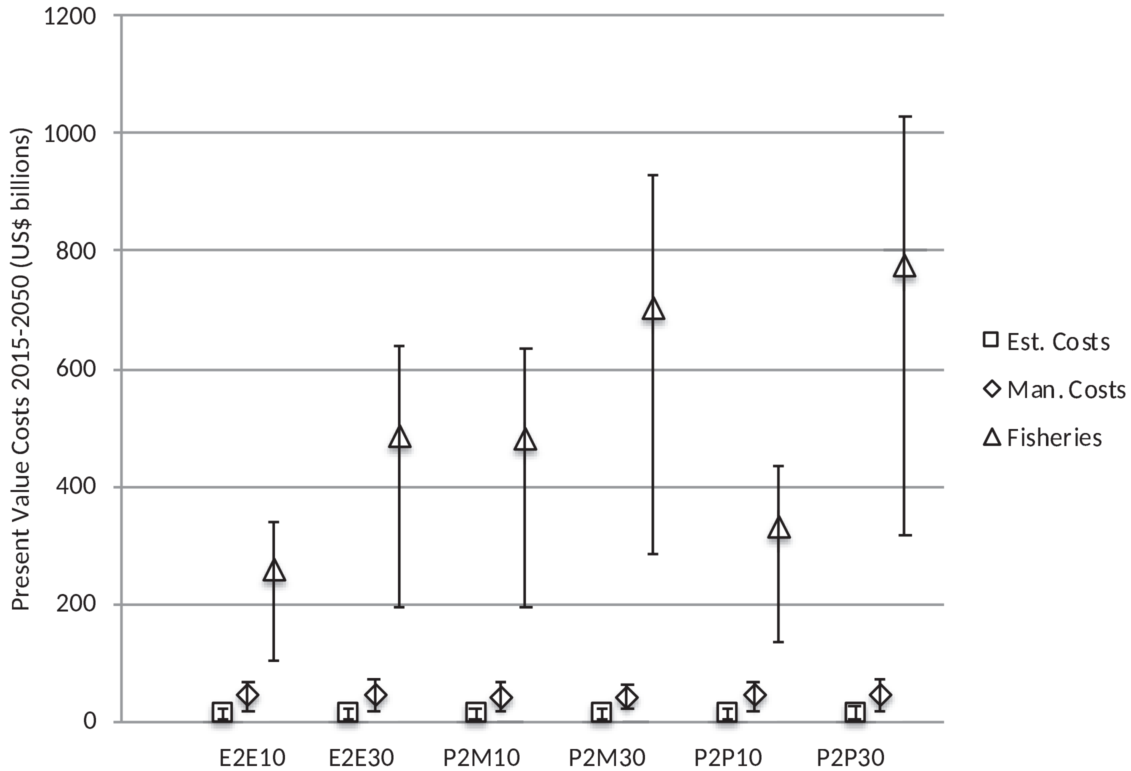
Figure 4. Benefits of expanding MPAs (US$; billions; 2020 price level; present values over the period 2015-2030 using a discount rate of 3%). Error bars represent 95% confidence intervals. Scenario acronyms: P2P "Protect to Preserve", P2M "Protect to Mitigate", E2E "Easy to Expand".

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".

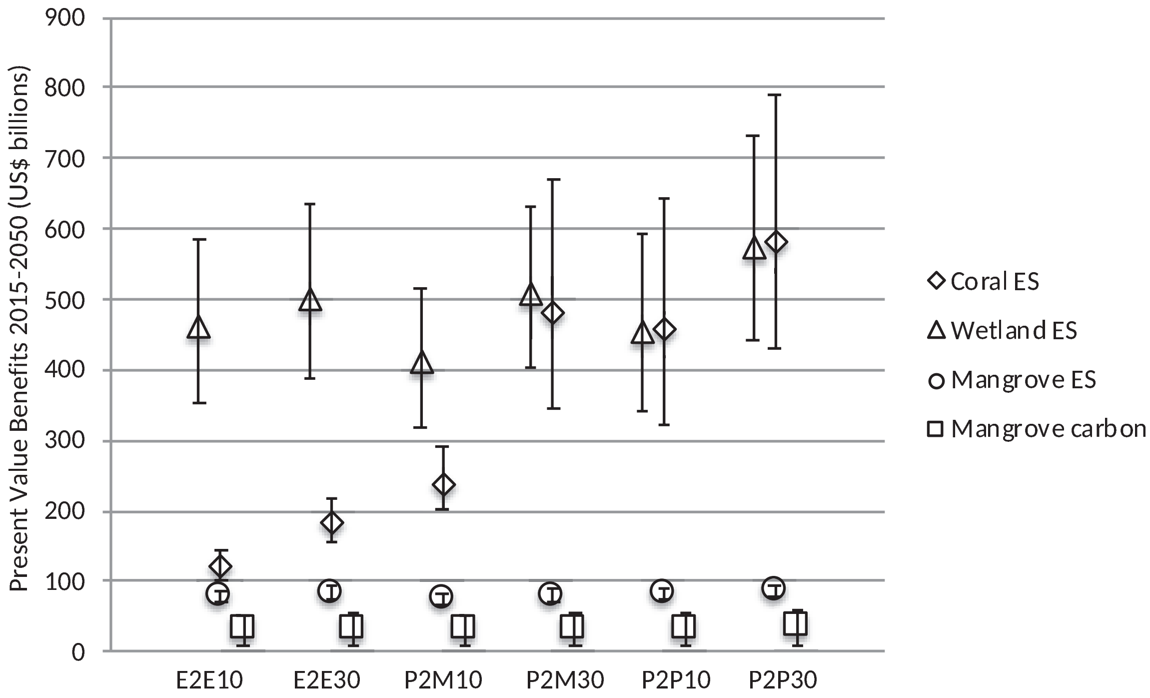
Figure 6. Benefit cost ratios (discount rate 3%). Error bars represent the combinations of high benefits-low costs (upper bound) and low benefits-high costs (lower bound) drawn from 95% prediction intervals for each cost and benefit. Scenario acronyms: P2P "Protect to Preserve", P2M "Protect to Mitigate",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


Lit. review of bio-physical impacts
Meta-analyses of ecosystem service values
Baseline Scenario Map
Changes in marine ecosystems and services
Value of changes in ecosystem services
Net benefits of MPA expansion
MPA Expansion Scenario Maps
Costs of MPA expansion scenarios
Lit. review of MPA costs


P2P
P2M
E2E
Current MPAs
P2P - 10% Expansion
P2P - 30% Expansion
P2M - 10% Expansion
P2M - 30% Expansion
E2E - 10% Expansion
E2E - 30% Expansion
Current Marine Protected Areas



1200
1000
800
600
400
200
0
Present Value Costs 2015-2050 (US$ billions)
E2E10
E2E30
P2M10
P2M30
P2P10
P2P30
Est. Costs
Man. Costs
Fisheries


900
800
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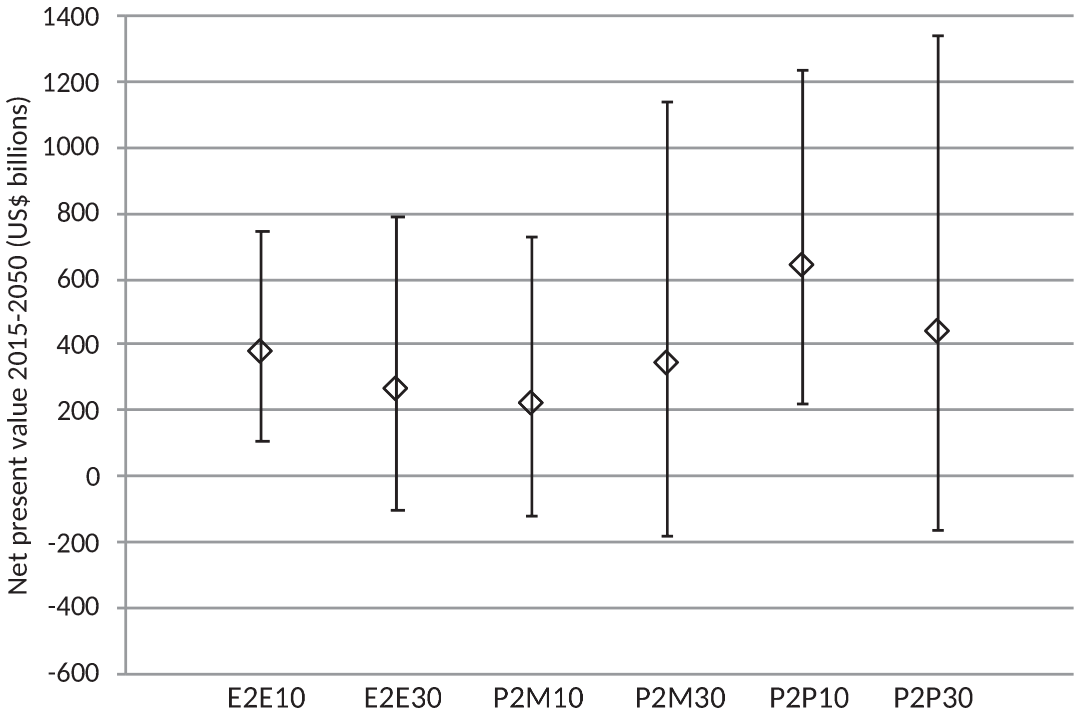
600
500
400
300
200
100
0
Present Value Benefits 2015-2050 (US$ billions)
E2E10
E2E30
P2M10
P2M30
P2P10
P2P30
Coral ES
Wetland ES
Mangrove ES
Mangrove carbon



Net present value 2015-2050 (US$ billions)
1400
1200
1000
800
600
400
200
0
-200
-400
-600
E2E10
E2E30
P2M10
P2M30
P2P10
P2P30

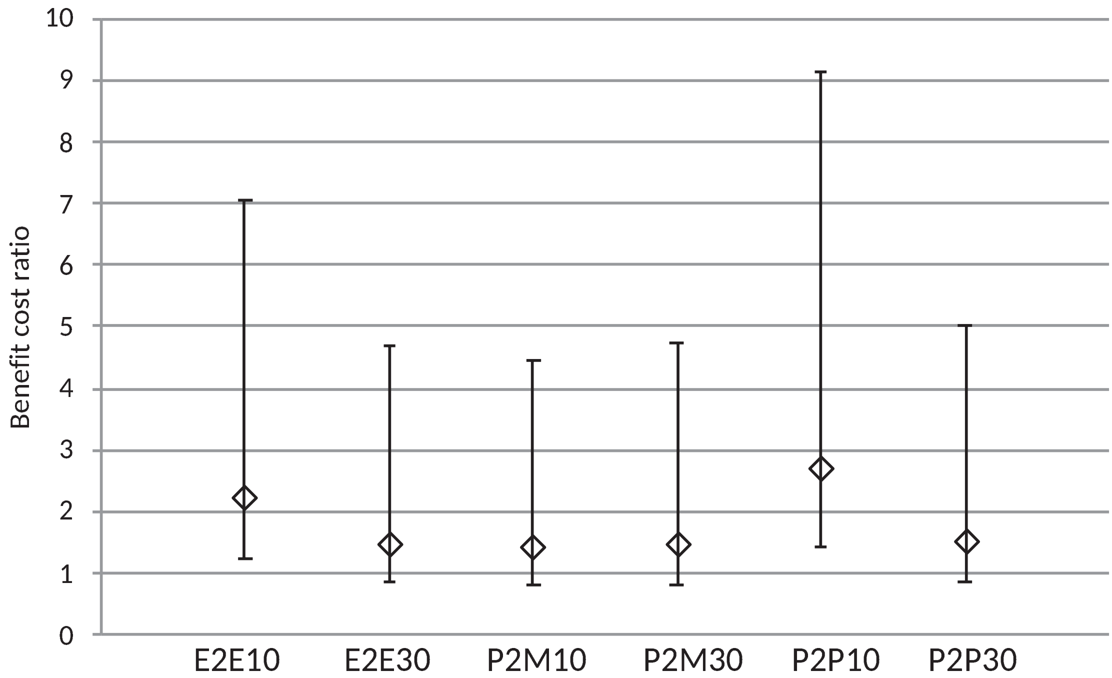

Benefit cost ratio
10
9
8
7
6
5
4
3
2
1
0
E2E10
E2E30
P2M10
P2M30
P2P10
P2P30

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