Received: 27 October 2022 | Accepted: 27 February 2023
DOI: 10.1111/gcb.16664

REVIEW

Global Change Biology WILEY

Making protected areas effective for biodiversity, climate and food

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Funding information
Helmholz Association

Abstract

The spatial extent of marine and terrestrial protected areas (PAs) was among the most intensely debated issues prior to the decision about the post-2020 Global Biodiversity Framework (GBF) of the Convention on Biological Diversity. Positive impacts of PAs on habitats, species diversity and abundance are well documented. Yet, biodiversity loss continues unabated despite efforts to protect 17% of land and 10% of the oceans by 2020. This casts doubt on whether extending PAs to 30%, the agreed target in the Kunming-Montreal GBF, will indeed achieve meaningful biodiversity benefits. Critically, the focus on area coverage obscures the importance of PA effectiveness and overlooks concerns about the impact of PAs on other sustainability objectives. We propose a simple means of assessing and visualising the complex relationships between PA area coverage and effectiveness and their effects on biodiversity conservation, nature-based climate mitigation and food production. Our analysis illustrates how achieving a 30% PA global target could be beneficial for biodiversity and climate. It also highlights important caveats: (i) achieving lofty area coverage objectives alone will be of little benefit without concomitant improvements in effectiveness, (ii) trade-offs with food production particularly for high levels of coverage and effectiveness are likely and (iii) important differences in terrestrial and marine systems need to be recognized when setting and implementing PA targets. The CBD's call for a significant increase in PA will need to be accompanied by clear PA effectiveness goals to reduce and revert dangerous anthropogenic impacts on socio-ecological systems and biodiversity.

KEYWORDS
climate change mitigation, food security, protected areas

1 | INTRODUCTION

Biodiversity loss and climate change are progressing at an alarming rate (IPBES, 2019). In response to this challenge, terrestrial and marine protected areas (PAs) are increasingly recognised as being central to biodiversity conservation (Coetzee et al., 2014; Davidson & Dulvy, 2017). Aichi Biodiversity Target 11 of the Convention on Biodiversity (CBD) was formulated with the aim of protecting 17% of the terrestrial surface and 10% of oceans by 2020. PAs are generally not only more species rich than neighbouring areas, they also contribute to avoiding species extinctions, habitat loss and degradation (i.e. also supporting the objectives in Aichi Biodiversity Targets 5, 6, 12, 14, 15). It is not surprising, therefore, that PAs feature prominently in the CBD's post-2020 Global Biodiversity Framework (GBF). As most of the Aichi targets have not been achieved (IPBES, 2019), this new framework seeks to increase global efforts towards biodiversity protection for the periods to 2030 and 2050.

The Kunming-Montreal GBF Target 3 calls for a very ambitious increase to at least 30% of land and marine areas to be protected by 2030. The UN Framework Convention on Climate Change has also recognised the co-benefits of nature protection for climate change mitigation in regions where biodiversity-rich and carbon-rich ecosystems correspond (Melillo et al., 2016; Soto-Navarro et al., 2020; see also e.g. the Glasgow Declaration of Forest and Land Use, https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/). Conversely, concerns have been voiced that a large expansion in PAs could compromise climate change adaptation in human societies and the provisioning of a broader set of ecosystem services, food in particular, due to PAs competing for space with other human uses (Henry et al., 2022; Mehrabi et al., 2018; Nakamura & Hanazaki, 2017).

PA coverage is a relatively easily measurable indicator of conservation effort. However, the effectiveness of PAs is critical for conservation success (Bhola et al., 2021; Butchart et al., 2015). Ignoring the two-dimensional space that defines PAs (that is: area *and* effectiveness) will limit their contribution to successful biodiversity outcomes. Target 3 of the GBF recognises 'effectively conserved and managed through ecologically representative, well-connected and equitably governed systems of PAs and other effective area-based conservation measures…'; however, (i) progress towards similar objectives set in the Aichi targets was weak and (ii) effectiveness is difficult to measure.

2 | THE NATURE'S GREEN SHOOTS FRAMEWORK AND VISUALISATION

The approach outlined here to visualise the synergies and trade-offs arising from PAs and their impacts on biodiversity, climate change mitigation and food production is inspired by the "Burning Embers" diagrams that are used to synthesise and communicate climate change risks for natural and human systems in assessment reports of the Intergovernmental Panel on Climate Change (IPCC) (O'Neill et al., 2017; Smith et al., 2009). Nothing similar exists for the biodiversity crisis. By focusing on risks, the Burning Embers do not identify the possible policy levers and sets of actions to reduce these risks. We propose, therefore, nature's 'Green Shoots', as a complementary approach to inform international biodiversity and climate change policies that goes beyond the identification of risks towards the analysis of solutions.

The *y*-axis in Figure 1 gives the global areal coverage of terrestrial or marine ecosystems within PAs. The analysis is separated into

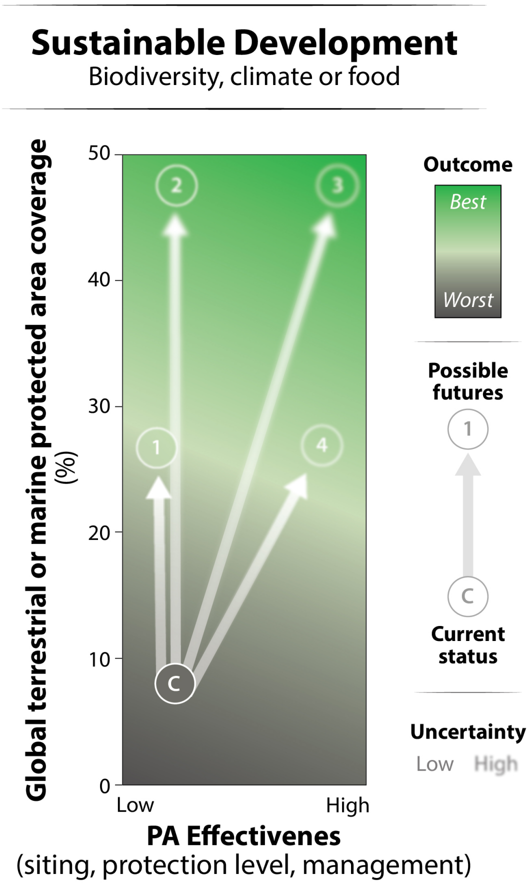


FIGURE 1 'Green Shoots' template as used for the analyses shown in Figure 2. The *y*-axis gives the global coverage of terrestrial or marine ecosystems in PAs (as a percentage) where the scale ranges from 0% to a maximum of 50%, which is the highest commonly cited figure for maximum global PA coverage (Dinerstein et al., 2017, 2019); the *x*-axis ranges from low to high level of effectiveness. "High" on the effectiveness scale indicates that most PAs are optimally sited, under strict protection (sensu IUCN PA categories I and II), well managed and adequately resourced. "Low" indicates that most PAs are sited in areas of low biodiversity value, have low levels of protection (sensu IUCN PA categories V and VI), are poorly managed and have insufficient financing. An encircled 'c' is used to represent the current global status of PA coverage and estimated effectiveness. Numbers '1' and '2' represent cases where (close to) 30% and 50% PA coverages are approached, respectively, without overcoming the barriers that affect current effectiveness levels. Numbers '3' and '4' represent cases where 30% and 50% PA coverage are approached, respectively, whilst overcoming current barriers to PA effectiveness. Increasing uncertainty of location of colour transitions are indicated by increasing fuzziness in the circles. Arrows are included here to guide the eye. Additional information: see Supplementary text and figures and Shoots_PA.xls (https://zenodo.org/record/7690684).

terrestrial and marine realms because of their different pressures, functioning and governance structures. When assessing solutions, a second dimension is required. The *x*-axis thus gives the "effectiveness" of PAs, which is defined here as a combination of three important enabling conditions: *where* PAs are sited, *how* PAs are managed, and the ability or capacity per se to *implement* them. Combining these into a second dimension is interpreted as the need to ideally achieve all the three enabling conditions, that is, the scoring is low if any one of these three criteria is not met.

The colours in the graphics represent the outcomes of PA coverage and effectiveness for selected sustainable development objectives: in this case, biodiversity, climate and food. The colour gradient is set from grey, indicating the poorest outcome, to green that indicates the most positive outcome (see Supplement and Shoots_PA.xls; https://doi.org/10.5281/zenodo.7690684 for a further description of the method; an alternate colour scale is provided in the Figures SI-1 and SI-2, recognising colour vision deficiencies). The method assumes that PA coverage (*y*-axis) and PA effectiveness (*x*-axis) are independent in determining the overall outcome.

The colour transitions chosen are qualitative, and involve judgements made by the authors, informed by outcomes of assessment reports of the IPCC and IPBES (IPBES, 2019; IPCC, 2019) and by a large literature review (see text and Tables SI-1 and SI-2). Colours represent the outcome of a change in PA in relative terms, the default colour transition is linear but can be non-linear if supported by the literature. As one moves from the current status to areas towards the green end of the gradient the outcomes are considered to substantially improve for biodiversity conservation, climate change mitigation or food provisioning. As one moves towards the grey end of the gradient, outcomes are considered to become considerably worse. The Green Shoots approach allows exploration and visualization to communicate alternative scenarios of PA coverage and effectiveness that are widely discussed in the literature. For instance, 30% and 50% PA coverage may well be reached without overcoming the barriers that affect current effectiveness levels (e.g. resources, knowledge, political will; examples indicated by '1' and '2' in Figure 1). Likewise, 30% and 50% PA coverage may be reached whilst overcoming current barriers to PA effectiveness (indicated by '3' and '4', Figure 1). Note that the level of uncertainty in colour attribution rises for global PA coverage and effectiveness as they depart from current levels. We assess moderate-low uncertainties with identifying present-day conditions, and with the direction of the response (i.e. whether the implementation of a measure would lead to an overall positive or negative impact) reflecting the paucity of quantitative information at a global-scale level regarding biodiversity and ecosystem responses to the measures addressed in this review.

Our analysis focuses on the global scale. Likewise, the judgements underpinning colour transitions are made without considering other changes such as human population growth or climate change impacts, which would influence how PAs interact with biodiversity, food production, or carbon uptake and storage. The Green Shoots are designed flexibly (*Shoots_PA.xls*) to allow such additional aspects to be factored in and may also be applied at regional or national scales, given that synergies and trade-offs arising from increasing PA coverage and effectiveness will differ between social-ecological contexts and geographic regions.

3 | CURRENT STATUS OF PAs

Terrestrial protected areas (TPA) currently cover about 15% of the Earth's ice-free, land surface and achieving this coverage by 2020 was one of the very few near successes of the Aichi Biodiversity Targets set in 2010 (Belle et al., 2018). However, the current TPA network is insufficient to cover a significant amount of the geographical range of most known plant and animal species (Butchart et al., 2015; Venter et al., 2018). For todays' TPA network, one estimate is that <70% of bird and mammal species, <35% of reptiles and amphibians have adequate representation (Allan et al., 2019). Of vertebrates threatened with extinction, only 19% of their range is represented on average (Montesino Pouzols et al., 2014).

The overall success of TPAs in terms of nature conservation is reduced by inadequate management and siting (Venter et al., 2018). TPAs are often placed in areas with limited human-use potential, rather than areas of high biodiversity value (Pimm et al., 2018; Venter et al., 2018). Earlier estimates of average management effectiveness varied between 45% and 55% (Coetzee et al., 2014; Leverington et al., 2010). Others have found that less than 25% of TPAs have adequate financial and staff capacity to achieve their objectives, resulting in only 4%–9% of terrestrial mammals, amphibians and birds having ranges that were protected by those TPAs that have sufficient resources (Coad et al., 2019). For forests, when shortcomings in effectiveness are taken into account, only 6.5% can be considered protected (Wolf et al., 2021). While there is agreement that TPAs have been somewhat effective in avoiding land conversion and that species diversity is higher inside than outside TPAs (Coetzee et al., 2014), our overall assessment of today's effectiveness is of the order of 20% between lowest and highest (Figure 2 'c').

Likewise, evidence from the literature shows that the global network of marine protected areas (MPAs) underperforms and therefore sits at the low end of the effectiveness scale, similar to the TPAs (Figure 2). Observed MPA coverage is presently about 7.5% of coastal and marine waters (Maxwell et al., 2020), but with at most only half being truly implemented (Gill et al., 2017; Maxwell et al., 2020; Sala et al., 2021). Among these, only 71% were found to be effective to some extent (Gill et al., 2017; Sala, Lubchenco, et al., 2018). The current system of MPAs falls short in providing adequate coverage of species geographical ranges (Davidson & Dulvy, 2017; Guilhaumon et al., 2015; Mouillot et al., 2011) and the diversity of ecosystems (Maxwell et al., 2020). In addition, a significant proportion of those MPAs do not have the sufficient levels of size and protection (Claudet, Loiseau, et al., 2020; Zupan et al., 2018), management

FIGURE 2 Impacts of terrestrial (top) and marine (bottom) protected areas on biodiversity, climate and food. The *y*-axis is the percent of global areal extend terrestrial or marine ecosystems in PAs where the scale ranges from 0% to a maximum of 50%. The *x*-axis, effectiveness: represents (i) siting (i.e. how well PAs are sited based on biodiversity criteria alone), (ii) protection level (i.e. how well the type and amount of impacting human activities are regulated within the PA) and (iii) management effectiveness. Today's status is indicated by a 'c'. 'Biodiversity': intends to integrate across all domains of biodiversity, but most terrestrial literature relates to species diversity or abundance, with a focus on gamma diversity. Most marine studies use protected fish species biomass as the most common indicator when studying PA performance. 'Climate': climate change mitigation through maintenance of marine or terrestrial ecosystems and increase of ecosystem carbon stocks. 'Food': estimated by fishing yield per effort (marine) and land area available for crop production (terrestrial). Colour transitions are based on an assessment of the literature (see text and Supporting information), uncertainties for the present day are medium-low and increase when moving towards higher area coverage and, especially, higher effectiveness. Uncertainty in the Green Shoots is largest in the top right corner of each diagram, which is farthest from the situation today.

capacity (Gill et al., 2017) or enforcement (Guidetti et al., 2008) to be fully effective (Tables SI-1 and SI-2).

4 | PROTECTED AREA TARGETS FOR 2030–2050

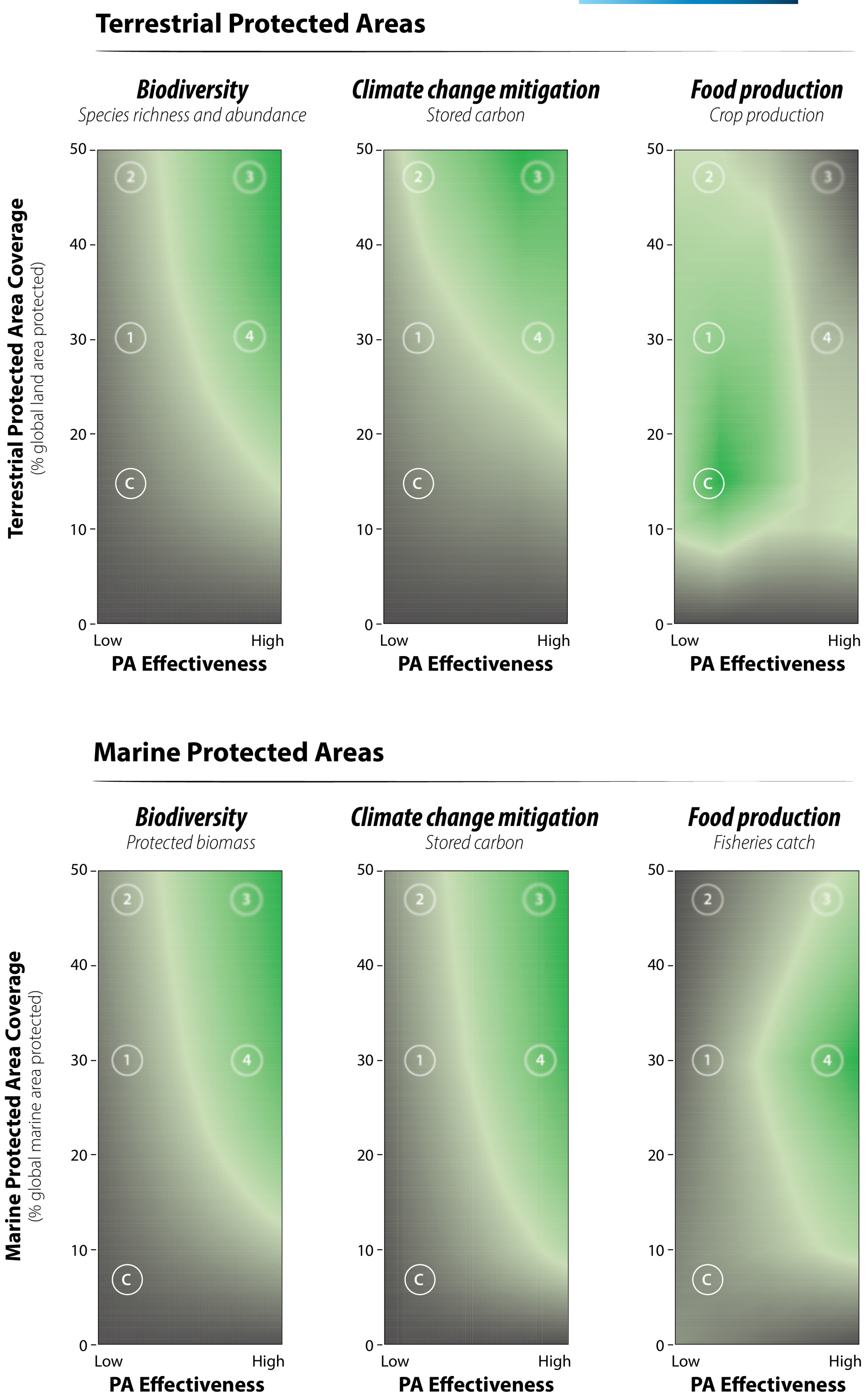
Increasing both the coverage and effectiveness of TPAs and MPAs over the coming decades would help to slow the loss of biodiversity. There are, however, on-going debates about (i) the emphasis on increased area vs. improved siting, protection levels and management (Claudet, Loiseau, et al., 2020), (ii) the fraction of land or ocean that would be desirable to include in protected areas (Butchart et al., 2015; Dinerstein et al., 2019), and (iii) the contribution of other effective, area-based conservation measures (Dudley et al., 2018; Gurney et al., 2021).

Some argue that as much as half of the Earth's ice-free land surface should be set aside for PAs to ensure adequate protection of species and ecosystems (Dinerstein et al., 2017), considerably exceeding the adopted Target 3 of the GBF. The argument behind 'Half Earth' draws on studies showing that 85% of plant species could be protected in this way (Joppa et al., 2013), which others extended to ca. 85% of all species based on relationships between species and required habitat area (Dinerstein et al., 2017). There is considerable debate about the degree of protection that should be conferred on these areas: proposals include relatively strict protection from human activities, while others suggest an approach that would allow for sustainable use of biodiversity alongside agricultural activities (Balmford et al., 2018; Dinerstein et al., 2019; Dudley et al., 2018; Rasmussen et al., 2018). Under some assumptions, even at the highest level of effectiveness, a TPA of 50% would not cover all plants (Pimm et al., 2018) and all mammals (which potentially would require 60% of all land; Mogg et al., 2019).

While these estimates in themselves are controversial (Pimm et al., 2018; Wilhere, 2021) the importance of increasing today's TPA effectiveness and need to overcome shortcomings regarding financing, management or placement is still not central to the debate (Butchart et al., 2015; Pimm et al., 2018), although some studies have argued that the primary emphasis indeed should be on increasing effectiveness given limited land resources (Adams et al., 2019; Nicholson et al., 2019; Visconti et al., 2019). Thus even for 30% coverage, protection has been estimated to provide major improvements in coverage of all species (including non-vertebrates) and ecoregions (Butchart et al., 2015, 2016; Di Minin et al., 2016; Jenkins et al., 2013; Montesino Pouzols, et al., 2014) only when TPA effectiveness is considered an essential component of this target.

With respect to siting, different perspectives on biodiversity (e.g. species diversity, endemism, ecosystem intactness) can lead to very different PA configurations, which will result in different sets of co-benefits and trade-offs. Nevertheless, siting of TPA networks could acknowledge different biodiversity priorities through improved spatial planning to prioritize areas of high biodiversity value jointly with ecological representativeness (Adams et al., 2019; Nicholson et al., 2019; Visconti et al., 2019). We reflect these views in Figure 2 such that at high effectiveness, protection of biodiversity rapidly improves with increasing TPA coverage, but with diminishing returns (Butchart et al., 2015; Geldmann et al., 2018) (smaller benefits as TPA percentage increases above ca. 30%; Figure 2, Shoots_PA.xls in the Supplement). Such a diminishing return is expected as, for example, increasing TPA coverage results in higher levels of connectivity (Santini et al., 2016; Saura et al., 2018), and TPAs increasingly capture whole foodwebs and communities (rather than species) (Mori et al., 2018). However, if resources to establish and manage TPAs remain limited, expanding to 30% or even 50% TPA coverage will barely enhance biodiversity protection, and even be poorer than 20% TPA coverage with resources dedicated to increased effectiveness. The minimum value is set to occur at 0% protected areas, while the maximum value (dark green) occurs at 50% protected areas with high effectiveness.

As with TPAs, MPAs can lead to significant conservation outcomes such as increases in fish density, size, and biomass (Zupan et al., 2018), as well as in species richness and functional rarity (Mouillot et al., 2008), and restore food webs and habitats (Babcock et al., 2010; Guidetti & Sala, 2007). While the literature on TPAs focuses mostly on impacts on species richness or abundance, protected fish species biomass is most commonly used in marine studies as an indicator for evaluating MPA performance (Figure 2; Shoots_PA.xls). In marine systems, fish biomass has been shown to be among the strongest predictors of fish species diversity and therefore a useful proxy (Duffy et al., 2016). The biodiversity benefits of MPAs vary greatly in magnitude depending on coverage or effectiveness. As for TPAs, siting (Sala et al., 2021) and management (Gill et al., 2017) play a major role. MPA effectiveness has also been shown to be strongly dependent on the MPA levels of protection


Terrestrial Protected Areas
Biodiversity
Species richness and abundance
Climate change mitigation
Stored carbon
Food production
Crop production
Terrestrial Protected Area Coverage
(% global land area protected)
50
40
30
20
10
0
2
3
1
4
C
Low
High
PA Effectiveness
Marine Protected Areas
Biodiversity
Protected biomass
Climate change mitigation
Stored carbon
Food production
Fisheries catch
Marine Protected Area Coverage
(% global marine area protected)

(Horta e Costa et al., 2016), with positive outcomes mostly observed for fully or highly protected areas (high end of effectiveness axis) and barely observed for lower levels of protection (low end of effectiveness axis) (Zupan et al., 2018). Hence, if the levels of protection are too low (Grorud-Colvert et al., 2021; Zupan et al., 2018), the management capacity insufficient (Gill et al., 2017), or MPAs poorly placed (Guilhaumon et al., 2015), MPAs barely deliver positive outcomes, even at large coverage of 30% or even 50%.

When considering well-functioning MPAs, positive biodiversity outcomes generally increase locally with MPA size and regionally with overall coverage (Davidson et al., 2017; O'Leary et al., 2016). A recent synthesis proposed that at least 30% of the oceans should be covered by PAs to efficiently protect biodiversity, ensure population connectivity among MPAs and population persistence (O'Leary et al., 2016), and minimize the risk of fisheries and population collapse and ensure population persistence (O'Leary et al., 2016). Achieving 30% protection would also help mitigate the adverse evolutionary effects of fishing, maximize or optimize fisheries value or yield, and thus satisfy multiple stakeholders (O'Leary et al., 2016). The rate of biomass increase within MPAs is expected to be sharp up to 30% global coverage with a lower increase for higher coverage, up to 50% (Grorud-Colvert et al., 2021; O'Leary et al., 2016).While increasing MPA coverage up to 50% of the global oceans is being debated, this target so far lacks a strong scientific basis for a proven increase in performance.

5 | PA IMPACTS ON CARBON UPTAKE AND STORAGE, AND FOOD PRODUCTION AND FISHERIES

On land, areas of high biodiversity and high carbon stocks can correspond, notably in many pristine forests, wetlands and savannahs (Soto-Navarro et al., 2020). Protection of valuable areas that are still largely intact creates therefore climate change mitigation co-benefits by avoiding potentially large carbon losses while also maintaining substantial, extant carbon sinks (Finlayson & Gardner, 2021; Soto-Navarro et al., 2020; Zhou et al., 2022). Conservation actions that target biodiversity-rich areas that are already under threat can provide additional biodiversity-carbon co-benefits, albeit at a smaller scale (Soto-Navarro et al., 2020). Avoiding further conversion of these areas into land used for agricultural production is important given that only between 12% and 21% (depending on the choice of biodiversity indicator) of joint carbon and biodiversity "hotspots" are currently protected, while carbon losses from the conversion of natural land continue to be substantial ('current', Figure 2) (Friedlingstein et al., 2020; Soto-Navarro et al., 2020). The restoration of ecosystems will achieve further positive synergies for both species and carbon pools, if both goals are pursued simultaneously (Strassburg et al., 2020). That is why an increase in TPAs to, for example, 30% may only provide modest climate mitigation benefits at current levels of effectiveness, since little protection of carbon stocks and sinks would be provided. Positive impacts increase rapidly as the effectiveness of protection increases (Mehrabi et al., 2018). However, this does not mean that no trade-offs exist. If the selection of TPAs is based on strict biodiversity considerations (i.e. highest effectiveness), the carbon benefits would not be equivalent since biodiversity and ecosystem carbon sinks are not perfectly co-located across all world regions (and the degree of correspondence depends also on the definition of biodiversity conservation priorities; Soto-Navarro et al., 2020; Strassburg et al., 2020). Even at 50% TPA, carbon sequestration would be expected to be somewhat lower when, for example biodiversity hotspots are given priority, compared to siting that accounts for the co-location benefits (Soto-Navarro et al., 2020; Strassburg et al., 2020). As such, the optimal solutions for climate would be large areas being protected at, from a biodiversity perspective, medium-to-high effectiveness (Figure 2).

Protected areas can hamper the ability to produce, harvest and trade food and fibre, especially if these activities are fully excluded from PAs. Given that considerably more than 50%, of the ice-free land surface is already used for food, feed, fibre and timber production, and millions of people remain undernourished (IPCC, 2019), conflict with expanding TPAs is inevitable. While new TPA could all be placed in unproductive regions this would be contradictory with the goal of improved TPA siting. Relatively low TPA coverage reduces global competition for land, which is advantageous for food production. However, TPAs provide watershed protection and habitat for pollinators, support traditional farming systems and act as reservoirs for genetic resources (Borelli et al., 2020; Senapathi et al., 2015; Watson et al., 2019), such that absence of TPAs would diminish global food production (Figure 2). Current land use has developed with a primary focus on agricultural productivity. Today's TPAs do not limit production, while providing benefits to surrounding agricultural regions and therefore are represented as broadly beneficial ('current', Figure 2) for global production. At very low TPA efficiency, their beneficial roles are unlikely to be realised even with high PA coverage, even though land area competition is modest in 'paper parks' (Di Minin & Toivonen, 2015).

The level of protection but also the location affects the resulting trade-offs. Protection of primary ecosystems stops agricultural expansion into these areas but does not require reconfiguration of the current food system (i.e. changes in existing demand or production). However, the extent of such ecosystems not already protected is limited, and the ongoing biodiversity loss requires expanding TPAs in productive agricultural regions. Conflicts over land resources therefore will likely become acute if PA coverage were to increase substantially, especially if the level of protection increased and/or if protected areas were placed where both agricultural and biodiversity values are high (Henry et al., 2022; Mehrabi et al., 2018; Schleicher et al., 2019). Food could, in principle, be produced on less agricultural land by increasing the intensity of agricultural production (i.e. land sparing; Phalan et al., 2011). But the impacts of TPAs on food security at very high levels of coverage (i.e. both 30% and 50% TPAs) with a strong conservation focus (i.e. strict protection) could increase food price increases and food insecurity (Henry et al., 2022; Kok, 2020; Mehrabi et al., 2018), reflecting higher costs of inputs arising from production intensification. Higher food prices would be most severe for poorest globally and add to rates of malnutrition (Henry et al., 2022; Kok, 2020). Increasing agricultural water withdrawals and pollution from greater fertiliser and pesticide use (Balmford, 2021; Henry et al., 2022; Mehrabi et al., 2018; Rasmussen et al., 2018) would have negative biodiversity and societal consequences in the remaining agricultural areas (Balmford, 2021; Henry et al., 2022; Rasmussen et al., 2018).

The climate change mitigation benefits of establishing MPAs are mostly the result of protected and enhanced marine carbon pools, commonly referred to as Blue Carbon (Lovelock & Duarte, 2019; Mcleod et al., 2011; Moraes, 2019). So far, only three marine ecosystems (mangroves, seagrasses and tidal saltmarshes) have been officially recognized by the IPCC as blue carbon sinks, and can count towards countries Nationally Determined Contributions (NDCs). These are also biodiversity-rich ecosystems. However, other important carbon pools such as marine animals and marine sediments are receiving increasing attention (Estes et al., 2019; Lovelock & Duarte, 2019). MPAs can contribute to climate change mitigation by increasing blue carbon pool sizes, which occurs when protection allows ecosystems to recover. Just as for other MPA outcomes, climate benefits heavily depend on MPA effectiveness. Indeed, low levels of protection fail to protect sediments and the sequestered carbon from trawling (Oberle et al., 2016; Pusceddu et al., 2014), and fail to increase fish biomass (Zupan et al., 2018), an essential link to export carbon to deeper waters and seafloor sediments (Saba et al., 2021). For the effect of area coverage on carbon sinks, it is expected that strong gains would be obtained with a small coverage of strategically placed MPAs on specific carbon pools. Indeed, an estimated 3.6% of ocean protection would allow protection of most of the currently trawled area (Sala et al., 2021), and coastal vegetated ecosystems only cover 0.2% of the ocean surface (Duarte et al., 2013). Additionally, the most carbon rich sediments are concentrated in the shallow seas, which represent only 21% of the ocean area (Atwood et al., 2017). However, several species-rich marine ecosystems, such as coral reefs, do not store substantial amounts of carbon. Hence, the overall positive climate outcome of MPAs would be somewhat diluted if MPAs were sited only according to biodiversity considerations. As such, the response curve of carbon sequestration benefits to the level of effectiveness has similarities with that of biomass benefits, such that little or no benefits are obtained at low levels of protection, steep increases are expected with increasing level of protection and effectiveness, and slower increases after the 30% coverage is met, when all Blue Carbon ecosystems are protected.

The proportion of overexploited (34.2%) and maximally sustainably exploited marine fish stocks (59.6%) has reached unprecedented levels (FAO, 2018), illustrating once more that both coverage and effectiveness of today's MPAs are insufficient to contribute to food security (point 'c', Figure 2). In most cases, food production, expressed here as fisheries catch, increases as MPA coverage increases because of the spill-over of adults and the export of eggs and larvae outside of MPAs (Di Lorenzo et al., 2020)—unless the level of protection effectiveness is too low to significantly reduce fishing mortality. Larger fish inside MPAs produce more offspring per unit of body mass than smaller fish and export of this increases production outside of an MPA resulting in much higher yields for fishing fleets in neighbouring areas (Marshall et al., 2019). MPA benefits for food are expected to be the highest at around 30% coverage, where increased catches outside MPAs can offset lost fishing grounds. At higher coverage, catches are expected to decrease due to a squeezing effect, where fishing effort concentrates in reduced fishing grounds (Cabral et al., 2019). However, if political and socioeconomic constraints are prioritized over biodiversity considerations in MPAs, some studies point to the possibility of fully protecting the whole areas beyond national jurisdiction—62% of the surface of the global ocean. Given that more than half of the high-seas fisheries would not be profitable without government subsidies, this could be achieved by removing subsidies (Claudet et al., 2021; Sala, Mayorga, et al., 2018; Wright et al., 2018), but studies to estimate the gains for biodiversity, climate and food of such a measure are required.

6 | SYNERGIES AND TRADE-OFFS BETWEEN BIODIVERSITY, CLIMATE AND FOOD

Reversing the loss of biodiversity, mitigating climate change, and sustainably feeding a growing human population are three critical and highly interlinked challenges. Since the magnitude of the problem is well understood, the scientific community is increasingly tasked with identifying solutions to support international policies (Claudet, Bopp, et al., 2020; Minx et al., 2017). The Green Shoots visualisations in Figure 2 are intended to synthesise information across a range of challenges and indicators and thus to provide a globally-integrated means of evaluating the usefulness of a policy measure in achieving multiple environmental or societal goals at the biodiversity-climate-food nexus.

From the literature, we assess the overall biodiversity response of TPAs and MPAs to increases in both extent and effectiveness to be broadly similar (Figure 2). TPAs and MPAs with weak management clearly are of little or no help in protecting biodiversity (Butchart et al., 2015; Guilhaumon et al., 2015; Horta e Costa et al., 2016; Montesino Pouzols et al., 2014; Zupan et al., 2018), which underpins the importance of committing resources and political will to improve PA effectiveness. Target 3 of the GBF, which aims to increase both TPA and MPA to 30% of the land area and coastal and marine waters, is supported by scientific evidence only if PAs are implemented in an effective way. The significant disconnect that exists at present between what is being pledged by governments in terms of resources to do so, and what is available in reality for implementing conservation measures is therefore of concern.

The Green Shoots as presented here support the growing consensus of better integration of the CBD and UNFCCC policy targets. Consequently, 30% or 50% PAs with high effectiveness can contribute substantially to climate change mitigation. It is important to note, however, that nature-based solutions for climate change mitigation, such as maintaining and enhancing carbon uptake and storage in marine and land ecosystems, are not alternatives to phasing-out fossil-fuels.

Synergies between increased PA coverage and food production exist, but trade-offs are unavoidable, with differences emerging between MPAs and TPAs concerning effectiveness and total PA coverage. In the ocean, at the lowest levels of effectiveness, MPA area-benefits for food supply will be negligible, while TPAs that are not protected well allow agricultural activities—even though TPA-crop yield benefits arising from for example pollinator protection may be small. At very high levels of effectiveness, and high coverage, PAs can negatively impact food security—the trade-off in this case being markedly greater for TPAs than MPAs. The combination of 30% PA coverage at high levels of effectiveness is highly beneficial for the supply of seafood, but may already compromise food production on land. The challenges arising from the competition for land between nature protection and food production could, however, be addressed by reducing food losses and wastes and by changing diets (Henry et al., 2019; Smith et al., 2020). This would also contribute to more equitable global food distribution (Smith et al., 2020). Reducing food waste and striving for globally equitable supply would also have benefits for marine systems, and the societies that depend on them.

The trade-offs between biodiversity and food production are strongly influenced by how PA coverage is increased. TPA expansion into areas that are still predominately natural would have relatively little impact on food production, but TPA expansion through ecosystem restoration on agricultural land would have large impacts on food. Given the need to feed a growing population, large-scale, ecosystem restoration on agricultural land is challenging, although for some national contexts PA expansion through restoration may be relevant, at smaller scales.

The choices made now about PA extent can tip the balance toward either negative or positive outcomes across nexus challenges—such as demonstrated here for biodiversity, food and climate. Urgent action is needed to avoid dangerous levels of anthropogenic interference both in the climate and socio-ecological systems, but it is important to get these actions 'right', especially since some of the benefits will accrue only with time. Our analysis in principle supports the 30% PA target in the GBF. For this target, cross-nexus co-benefits are achievable if PA effectiveness and coverage are prioritized equally. It will be essential, however, to adopt additional measures to avoid losses or overconsumption in the food system. Given siting, protection level and management effectiveness, national and global policy could foster the much-needed compromise between PA expansion through restoration and increased protection of remaining natural ecosystems. The former will have immediate impacts on food production on land while carbon and biodiversity benefits will only increase with time. The latter will have immediate biodiversity and carbon benefits, while impacts on food systems depend on many factors such as future population growth and the capacity to maintain or enhance production from existing agriculture and fisheries sustainably. For both restoration and protecting natural ecosystems, increasing PA effectiveness is as important, if not more so, than increasing PA coverage. Specifying, and even hitting, targets defined only in terms of area will not achieve biodiversity goals, nor will they create synergies with other sustainability objectives.

To reflect these findings, the area-target in the GBF will need to be accompanied by measures that clearly address the aspired effectiveness, along the lines of 'the majority of these areas should strive for highest levels of protection'—for example, equivalent to the current IUCN categories I and II. Equally important will be to address PA siting in terms of ecological representativeness and connectivity, while striving to include local users of land and sea in decision making. As with area targets, measures will need to be put in place to monitor effectiveness targets. Such measures could combine remote sensing and in-situ species monitoring, as used for area-based targets, with information on PA management plans, dedicated spending and the involvement of local communities to ensure societal engagement. Given the potential for trade-offs in the climate-biodiversity-food nexus, the most appropriate assessment of PA success would need to combine ex-post measures with regular ex-ante analyses and modelling in order to identify the dynamic changes in management that would be required in response to, for example, future socio-economic trends or climate change.

ACKNOWLEDGMENTS

The authors acknowledge the discussions and suggestions in an earlier draft of the manuscript received by Dr. Joel Smith. We thank Juliette Jacquemont for inputs on blue carbon ecosystems. AA, RF and MR are supported by the Helmholtz Association. JC was supported by BiodivERsA (METRODIVER) and Fondation de France. MC and YJS acknowledge funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 869300 (FutureMARES) and No 817578 (Triatlas). MC acknowledges support from the Spanish Research project ProOceans (RETOS-PID2020-118097RB-I00). PL acknowledges support from the LabEx BASC (ANR-11-LABX-0034). YJS acknowledges support from the Belmont Forum and BiodivERsA joint call under the BiodivScen ERA-Net COFUND programme (Sombee project, ANR-18-EBI4-0003-01). Jens Krause and Lauric Thiault helped with drawing Figures 1 and 2. This work acknowledges the 'Severo Ochoa Centre of Excellence' accreditation (CEX2019-000928-S). Open Access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article. The xls spreadsheet supporting the development of the Shoots visuals can be found under https://zenodo.org/record/7690684

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How to cite this article: Arneth, A., Leadley, P., Claudet, J., Coll, M., Rondinini, C., Rounsevell, M. D. A., Shin, Y.-J., Alexander, P., & Fuchs, R. (2023). Making protected areas effective for biodiversity, climate and food. *Global Change Biology*, *29*, 3883–3894. https://doi.org/10.1111/gcb.16664