

## Supplementary material

The Supplementary material includes the following information

- 1) Additional information on Figures 1 and 2. Figures S1 and S2 are similar in shape to Figures 1 & 2 but using different colours; Tables S1 and S2 with additional information extracted from the literature.
- 2) Excel graphs, *Shoots\_PA.xls*: These worksheets contain the chosen colour values, transitions and their justification, and underpin the Shoots panels in the main manuscript. Available at: <https://zenodo.org/record/7690684>

### 1) Additional information about the ‘Shoots’

We develop and apply the Green Shoots for the example of protected areas, which represents a prominent -and largely promising- action to support biodiversity conservation, with potential co-benefits for climate change. The framework is flexible and can be adapted to other measures in the biodiversity/climate change/food nexus.

The initial step when developing the colour transitions is an excel-spreadsheet (*Shoots\_PA.xls*), which serves as the ‘sparring’ platform to develop and justify the colour transitions, documenting the author-judgement made, and can serve as a template for further, similar-types of analyses. Colour transitions can be linear or non-linear. Colour values range from -100 (grey) to +100 (green) across the surface of the Shoot. As one moves from the current status to areas towards the green end of the gradient the outcomes are considered to 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 worse than they currently are for biodiversity. The numbers along the -100 to +100 are linked to the colour scale and are meant to guide the visualisation; they represent the authors interpretation of the outcome of a change in PA. For specific modelling analyses on e.g. country scale they in principle could also be linked quantitatively to concrete modelling results.

For effectiveness, the highest values correspond to i) very limited or no extractive use or tourism (corresponding to e.g., IUCN categories I-II), ii) placement of protected areas where they have the most benefit for biodiversity regardless of other current uses and iii) adequate financing, effective management and policing. The lowest values of effectiveness correspond to protected areas that do not target biodiversity hotspots or ecosystems that are important to protect, with protected areas allowing multiple use, placement often avoiding conflicts with other current land uses and weak management (‘paper parks’). For a high score, all three of these criteria have to be met at least to some degree (i.e. the work multiplicatively).

The scientific literature assesses the impacts of PA on biodiversity with different indicators. For terrestrial studies, these indicators are most often linked to species diversity and/or habitat intactness; most studies would address diversity in habitats and species therein (i.e. gamma diversity). In marine studies, protected fish biomass is the dominant indicator that is studied for PA performance. These indicators in both cases imply also positive impacts of PA on other dimensions of biodiversity (such as genetic diversity and community structures).

For climate change mitigation both, the maintenance of carbon-rich ecosystems as well as maintaining carbon sinks matter. The former in order to avoid large carbon emission, the latter are particularly important of these sinks are long-term (i.e. leading to carbon storage in sediments, long-lived vegetation or soils, rather than in fast growing plantation forests with low lifetime).

The impact of PAs on food supply is estimated as fisheries catch or crop yields. This is the most-direct impact, which can be further modified (enhanced or dampened) by many other aspects of the food supply chain, especially by losses and wastes. These latter aspects are not included in the drawn Shoots.

The draft colour surfaces in *Shoots\_PA.xls* were subsequently re-drawn for smoothing (*Figures 1 and 2*), using the *krige* function in the *gstat* (v2.0-8) R package. The colour scale has been chosen so as to be also discernible for readers with different colour vision deficiencies; below we also provide the panels in an additional colour scale (*Figure SI 1 and SI 2*).

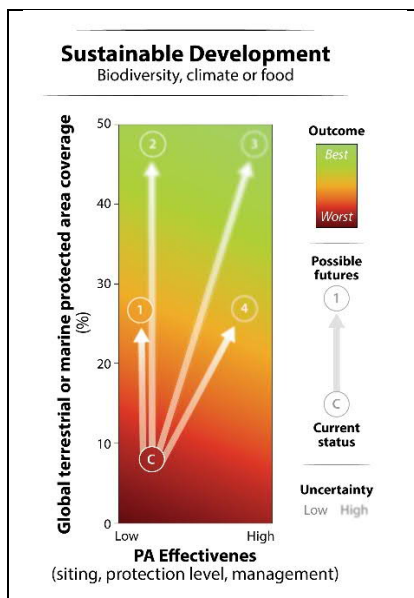


Figure SI 1: Generic ‘Green Shoots’ diagram template as used for individual aspects displayed in Figure 2. This is similar to Figure 1, but drawn in a different colour scale to accommodate readers with different colour blindnesses. The y-axis scale ranges from PA of 0% to a maximum of 50% as the highest commonly cited figure for maximum global PA coverage; the x-axis ranges from low to high level of effectiveness. An encircled ‘c’ represents the current global status of PA coverage and estimated effectiveness. Numbers ‘1’ and ‘2’ represent cases where the 30% and the 50% PA coverages are reached, respectively, without overcoming the barriers that affect current effectiveness levels. Numbers ‘3’ and ‘4’ represent cases where the 30% and the 50% PA coverage are reached, respectively, whilst overcoming current barriers to PA effectiveness. Increasing uncertainty of location of colour transitions are indicated by increasing fuzziness in the circles and arrows.

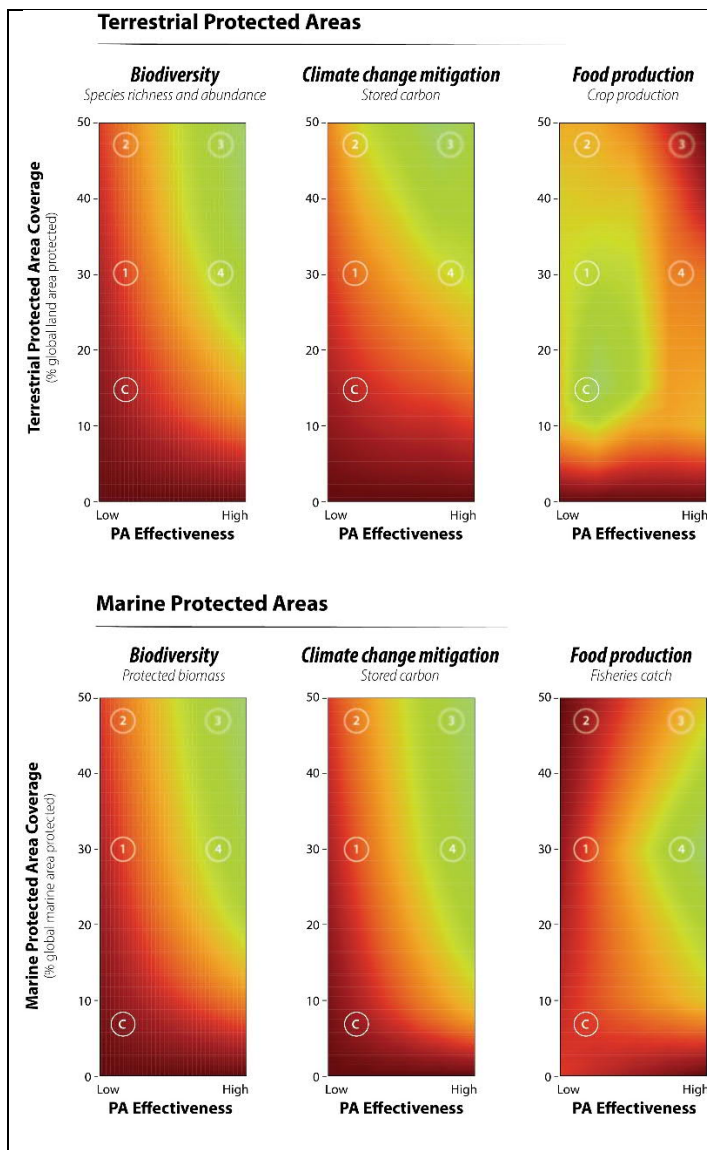


Figure SI-2: Impacts of Terrestrial (top) and Marine (bottom) protected areas. This is similar to Figure 2, but drawn in a different colour scale to accommodate readers with different colour blindnesses. The y-axis is the percent of global terrestrial or marine ecosystems in PAs where the scale ranges 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 is in fact related to species diversity or abundance, whereas most of the marine studies use protected biomass as the most common indicator. ‘Climate’: climate change mitigation through maintenance of marine or terrestrial ecosystems and increase of ecosystem carbon pools. ‘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, uncertainties for the present day are medium-low and increase when moving towards higher area coverage and, especially, higher effectiveness. In case of PAs, uncertainty in the Green Shoots is largest in the top right corner of each diagram.

## 2. Supplementary Tables

Tables SI-1 & SI-2 summarise the reviewed literature. In addition to key references cited in the main text and *Shoots\_PA.xls*, the data summarised in these tables was used to additionally support colour settings and transitions in these figures. 'Indicator' specifies whether the literature source was used to assess impacts on biodiversity (BD) or ecosystem services (ES); 'Scale' specifies the geographic extend of the literature source; 'Method' provides some information of the methodology of the source; 'Results' provides the main results extracted from the literature, separated by whether these were mainly used to support colour settings on the y-axis or x-axis (*or both*).

Table SI-1: Terrestrial Protected Area (ES: Ecosystem service)

Indicator	Scale (global, regional, local)	Method + (some details if needed, optional)	Results, relevant to y-axis	Results, relevant to x-axis	Ref.
Biodiversity	Global	Zonation used to identify the top 17% cells of the world that are top priorities for the conservation of taxonomic, functional and phylogenetic diversity of mammals		Overlap of all three components of biodiversity is 27.06%. Overlaps between pairs range between 37.64 and 52.35%. Taxonomic diversity only partially represents broader biodiversity even at the species level.	(Brum et al., 2017)
Biodiversity	Global	Gap analysis of terrestrial vertebrates plus identification of further sites to protect with Marxan and Rodrigues-like target	Less than half of the vertebrates achieve targets in current PA system. Coverage of KBAs is currently ca. 25%. An optimal solution could achieve targets for all terrestrial vertebrates, include KBAs, and represent ecoregions with ca 28% of the land protected.		(Butchart et al., 2015)
Biodiversity	Global	Gap analysis of ecoregions and natural habitat within	About half of the world's ecoregions are either above 50% of protection or still have more than 50% of natural habitat, which means that they could in theory reach it. The remaining half has less than 50% protection meaning that restoration would be necessary to reach 50% protection		(Dinerstein et al., 2017)
Biodiversity	Global	Review of published goals	50% protected is higher than most published goals		(Noss et al., 2012)
Biodiversity	Global	Species accumulation curves applied to regions from highest to lowest density of endemic plants	81% plants are concentrated in 17% of the land. The same regions contain 89% of the birds, 80% amphibians and 74% mammals		(Joppa, Visconti, Jenkins, & Pimm, 2013)
Biodiversity	Global	Marxan used to achieve either 17% target at minimum cost for each	Achieving targets for all vertebrates takes up as much land area (20.2%) as		(Oscar Venter et al., 2014)

		country or conservation target for each threatened vertebrate	achieving 17% for each country at minimum cost, but costs 7.5 times		
Biodiversity	Global	Marxan used to allocate recent (2004-2014) PAs optimally. Compared to actual new PAs		New PAs added protection for 85 new species of threatened vertebrates, while they could have been between 2553 and 3086 if new PAs were placed optimally	(O. Venter et al., 2018)
Biodiversity	Global	Synthesis of local studies; compare data from inside/outside PA (areas in close proximity)		Mean effect size using a random effects model across all 861 identified data: 0.44; IUCN categories 2 and 1, but also 5 had the most positive effect.	(Coetzee, Gaston, & Chown, 2014)
Biodiversity	Global	Synthesis of data and reports from previous PA effectiveness assessments		Mean score for management effectiveness: 0.53	(Leverington, Costa, Pavese, Lisle, & Hockings, 2010)
Biodiversity	Global	Analysis of management reports from 23% TPA		Ca. 25% of the TPA are sufficiently resourced, and 4-9% terrestrial amphibians, birds and mammals are sufficiently represented in TPA if resources are accounted for	(Coad et al., 2019)
Biodiversity	Australia	Scenarios of threat abatement for 1749 threatened species in Australian protected areas		Protected areas that are not well resourced can abate one threat for 76% of the species and all threats for 3%. Well-resourced PAs can abate one threat for 100% of the species and all threats for 48% of them. 52% of the species require coordinated efforts that protected areas alone cannot ensure	(Kearney, Adams, Fuller, Possingham, & Watson, 2020)
Biodiversity	Europe	Gap analysis on representation of geographic range, ESH or MVA for European large mammals		100% achieves representation targets for geographic range, but only 7.5-18% achieves targets for MVA	(Santini, Di Marco, Boitani, Maiorano, & Rondinini, 2014)
ES (Carbon – Terrestrial ecosystem	Global	Data and model analysis	Many ecosystems have both high biodiversity conservation value and high ecosystem carbon stocks and are not currently protected, so in these	Some biodiversity hotspots have low ecosystem carbon stocks, so biodiversity priority schemes will be	(Di Marco, Watson, Currie, Possingham,

carbon stocks)			cases increasing PAs would protect both biodiversity and ecosystem C stocks. For instance: Restoring 15% of converted lands in priority areas may avoid 60% of expected extinctions while sequestering 299 Gt CO <sub>2</sub> .	less efficient at protecting C stocks than carbon priority schemes	& Venter, 2018; Soto-Navarro et al., 2020; Strassburg et al., 2020; Strassburg et al., 2010)
ES (Carbon – Terrestrial ecosystem C storage)	Global	Scenario and model analysis	Meeting current targets for land restoration and protected areas would increase C storage by 50 Gt by 2030 and protect 28% of terrestrial area compared to business-as-usual scenarios		(Wolff, Schrammeijer, Schulp, & Verburg, 2018)
ES (Carbon – C emissions related to deforestation and forest degradation)	Global	Scenario and model analysis	Increasing budgets dedicated to forest protection (REDD+) greatly reduce deforestation related C emissions and biodiversity loss, with diminishing returns at high investment levels	Biodiversity priority schemes are less effective at reducing C emissions than carbon priority schemes	(Palomo et al., 2019)
ES (Carbon – Land-based climate mitigation potential)	Global	Synthesis	Avoided deforestation, reforestation and improved management in natural forests have very high potential for land-based C sequestration (up to 7 PgCO <sub>2</sub> e yr <sup>-1</sup> in 2030 with safeguards)		(Griscom et al., 2017)
ES (Food – crop food calories)	Global	Scenario and model analysis	Negative effects of PAs on crop food calories generally linear up to 50% of global terrestrial area protected	Strict protected areas have much larger negative impacts on crop food calories (-11% for global PA allocation and -29% for ecoregion PA allocation) than shared landscapes (0% and -3%)	(Ellis & Mehrabi, 2019; Mehrabi, Ellis, & Ramankutty, 2018)
ES (Food – costs related to land use conflicts with	Global	Scenario and model analyses	Increasing PA coverage inevitably increases overlap with agriculturally productive areas, but degree of	Effective placement of PAs for biodiversity value greatly increases overlaps agriculturally productive areas leading to a cost of creating PAs that is	(Venter et al., 2018)

agricultural land use)			overlap depends on PA placement and level of protection	7.5 times higher in optimal placement vs. cheapest placement	
ES (Food – costs related to land use conflicts with agricultural land use)	Global	Scenario and model analyses		Strictly protected 30% and 50% of land area results in food price increase (intensification, supply < demand), affecting consumption. Both positive (reduced overeating) and negative impacts (increase malnutrition). Net-negative: protection scenarios increase global mortality by further reducing fruit and vegetable consumption and maintaining higher levels of underweight related mortality (e.g. in 2060, 30% and 50% TPA increases total global mortality by 4% (eq. to an additional 31 and 28 deaths per million people)	(Henry et al., 2022)
ES (Food – agricultural revenues)	Global	Scenario and model analysis	Increasing PA coverage to 30% by 2050 can have small positive to large negative impacts on projected agricultural revenue depending on placement of PAs	Optimal PA placement for biodiversity results in substantial reduction in agricultural revenues	(FAO, 2014; Waldron et al., 2020)
ES (Food – food availability, diversity, crop production)	Global & Local	Global assessment + Local case studies (Costa Rica, Brazil, etc.)	PAs can play an important and positive direct and indirect roles in ensuring food security. PAs can increase crop production in adjacent areas through improved pollination, biological control of insect pests and other ecological synergies	Strict PAs can restrict access of local and indigenous peoples to important food sources	(Nakamura & Hanazaki, 2017; Sylvester, Segura, & Davidson-Hunt, 2016)
ES (Food – diet diversity)	Regional & local	Review, data from various countries and regions	Habitat destruction and food production systems that reduce availability of wild edible plants (pollution, removal of hedgerows..) negatively impact their nutritional benefits	Highest level of protection excludes people to harvest wild edible plants	(Borelli et al., 2020)
ES (Food - diet diversity)	Global – low and middle-income countries	Case studies in developing countries	Being near natural vegetation (forests in these cases) generally, but not always increases dietary diversity	In much of the dietary benefit comes from directly using forest resources that could be excluded in strict PAs	(Baudron et al., 2019; Sunderland & Vasquez,

					2020; Sylvester et al., 2016)
ES (Food-child nutrition)	Global – low and middle-income countries	Big data (i.e., aggregation of large data bases and sophisticated analysis)	Being near forests improves indicators of child nutrition		(Rasolofoson et al., 2020)
ES (Food, pollination)	Tropics	Synthesis of publicly available data + empirical modelling	80% of tropical protected areas contribute to crop pollination	Small size PAs esp. important due to vicinity to croplands, and because of larger perimeter:unit area	(Gutierrez-Arellano & Mulligan, 2020)

Table SI-2: Marine Protected Area

Indicator	Scale	Method	Results, relevant to y-axis	Results, relevant to x-axis	Ref.
Biodiversity (species density, species size, biomass)	Global	Meta-analysis	Ecological effectiveness of marine protected areas (MPAs) of various marine organisms.	Apply to the fully protected areas (high end of efficiency). Species density and biomass can increase up to 5-fold inside fully protected areas when compared to unprotected areas.	(Edgar et al., 2014; Lester & Halpern, 2008; Lester et al., 2009; Zupan et al., 2018)
Biodiversity (species density, species size, biomass)	Global	Meta-analysis	Ecological effectiveness of marine protected areas (MPAs) of various marine organisms.	Comparison of fully and partially protected areas (high end vs. lower efficiency). Species density, size, biomass and richness lower on partial protection compared to full protection.	(Lester et al., 2009)
Biodiversity (species density, biomass)	Global	Meta-analysis	Ecological effectiveness of marine protected areas (MPAs) of various protection levels.	Comparison of MPA levels of protection, age, and size. Species density and biomass can increase up to 3-fold inside highly protected areas when compared to unprotected areas. Species density and biomass can increase up to 3-fold inside moderately protected areas – if a fully protected area is present – when compared to unprotected areas. On average, MPAs of lower protection levels do not show positive benefits.	(Zupan et al., 2018)
Biodiversity (biomass)	Global	Meta-analysis	Ecological effectiveness of 87 MPAs investigated worldwide.	Conservation benefits increased exponentially with accumulation of five key features: fully protected, well enforced, old (>10 years), large (>100 km <sup>2</sup> ), and isolated by deep water or sand.	(Edgar et al., 2014)

Biodiversity (biomass)	Regional	Meta-analysis	Ecological effectiveness of 15 Italian MPAs.	Only MPAs that were well enforced were effective.	(Guidetti et al., 2008)
Biodiversity (species density of large individuals)	Regional	Meta-analysis	Ecological effectiveness of MPAs	Effect of MPAs increase with MPA age and size. For each year since protection, an increase of 8.3% mean relative density of commercial fishes was observed. For every 10-fold increase in the size of a no-take zone, an increase of density of commercial fishes of 35% was observed.	(Claudet et al., 2008)
Biodiversity/ES	Global	Synthesis; Multiple targets and objectives: to (1) efficiently protect biodiversity; (2) ensure population connectivity among MPAs; (3) minimize the risk of fisheries/population collapse and ensure population persistence; (4) mitigate the adverse evolutionary effects of fishing; (5) maximize or optimize fisheries value or yield; and (6) satisfy multiple stakeholders	Capacity to reach ecological targets	Increase with global coverage. Protecting several tens-of-percent of the sea is required to meet listed goals (average 37%, median 35%, modal group 21–30%). Listed goals met in 3% of studies with $\leq 10\%$ MPA coverage, 44% with $\leq 30\%$ coverage, and 81% with more than half the sea protected	(O'Leary et al., 2016)
Biodiversity (coverage of species geographical range)	Regional	Representatively and gap analysis	Capacity to encompass a sufficient proportion of each species geographical range	MPAs would be more effective if better sited. 70% of studied species did not achieve better protection in the current MPAs than expected from siting MPAs at random.	(Guilhaumon et al., 2015)
Food (Exported biomass)	Global	Review/ Meta-analysis. Model.	MPAs export biomass and can have fisheries benefits.	Found for fully protected areas and can be favoured in the presence of highly or moderately protected areas. An increase of 5% of MPA coverage globally would lead to an increase of 20% catch for constant fishing effort.	(Cabral et al., 2020; Di Lorenzo, Claudet, & Guidetti, 2016; Di Lorenzo, Guidetti,

					Calò, Claudet, & Di Franco, 2020)
Food (Exported biomass)	Regional	Meta-analysis	Spatial patterns of empirical estimates of 72 taxa of fish and invertebrates across the borders of 27 fully protected MPAs.	Prominent and consistent edge effect that extends approximately 1 km within the MPA, in which population sizes on the border are 60% smaller than those in the core area. MPAs with buffer zones did not display edge effects, suggesting that extending fully protected areas beyond the target habitats and managing fishing activities around MPA borders are critical for boosting MPA performance.	(Ohayon, Granot, & Belmaker, 2021)
Food (Exported eggs and larvae)	Model	Model	Exponential benefits of MPAs on the replenishment of fishing grounds with increased fish size in MPAs	In fully protected areas. Reproductive output inside fully protected areas can be increased by 139 to 175%.	(Marshall, Gaines, Warner, Barneche, & Bode, 2019)
Food (Exported biomass)	Model	Model	MPAs can protect global biodiversity.	MPAs can offset lost fishing grounds.	(Sala et al., 2021)
Food (catch)	Model	Model	Biomass within MPAs increase with MPA coverage.	MPA benefits on fisheries catch increase up to around 30% coverage and decrease at larger coverage.	(Cabral et al., 2019)
Carbon storage	Review	Review	MPAs provide a statutory approach for protecting blue carbon ecosystems.		(Lovelock & Duarte, 2019; Mcleod et al., 2011; Moraes, 2019)
Carbon storage	Model	Model	MPAs can protected C stored in marine sediments.	MPAs need to be of sufficient level of protection to prevent bottom trawling.	(Oberle, Storlazzi, & Hanebuth, 2016;

					Pusceddu et al., 2014; Sala et al., 2021)
Biodiversity, Food, Carbon	Review	Global	MPAs protect biodiversity, carbon stocks and can benefit fisheries.	MPA benefits increase with MPA levels of protection, management effectiveness and enforcement.	(Grorud-Colvert et al., 2021)

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