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Socio-economic and ecological impacts of global protected area expansion plans

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Several global strategies for protected area (PA) expansion have been proposed to achieve the Convention on Biological Diversity's Aichi target 11 as a means to stem biodiversity loss, as required by the Aichi target 12. However, habitat loss outside PAs will continue to affect habitats and species, and PAs may displace human activities into areas that might be even more important for species persistence. Here we measure the expected contribution of PA expansion strategies to Aichi target 12 by estimating the extent of suitable habitat available for all terrestrial mammals, with and without additional protection (the latter giving the counterfactual outcome), under different socio-economic scenarios and consequent land-use change to 2020. We found that expanding PAs to achieve representation targets for ecoregions under a Business-as-usual socio-economic scenario will result in a worse prognosis than doing nothing for more than 50% of the world's terrestrial mammals. By contrast, targeting protection towards threatened species can increase the suitable habitat available to over 60% of terrestrial mammals. Even in the absence of additional protection, an alternative socio-economic scenario, adopting progressive changes in human consumption, leads to positive outcomes for mammals globally and to the largest improvements for wide-ranging species.

1. Introduction

Protected areas (PAs) are considered the cornerstone of biodiversity conservation. In recognizing their role for the protection of species and ecosystems, the Convention on Biological Diversity (CBD) Aichi target 11 [1] requires countries to set aside land for conservation to protect 17% of the terrestrial realm and 10% of the marine realm by 2020 [2]. This target also specifies that the resultant PA network should be ecologically representative, a requirement that has been commonly interpreted as protecting 17% of each ecoregion [2]. Since the adoption of the Aichi targets in 2012, global terrestrial PAs have expanded from 10.9% to 14.6% on land and from 2.3% to 2.8% in the sea [3,4]. At this pace, the global coverage of 17% of land is likely to be met by 2020, while the target of 10% protection of coastal and marine environments will not [5]. In addition, progress towards producing ecologically representative PA networks has been slow, with only 41% of terrestrial ecoregions and 32% of marine ecoregions achieving the designated targets [3].

Several studies have proposed methods to prioritize further PA expansion to achieve the Aichi targets while minimizing socio-economic costs. Venter *et al.* [6] identified PA networks that would meet targets for threatened terrestrial vertebrate species and terrestrial ecoregions at minimum agricultural opportunity costs. Butchart *et al.* [3] did a similar analysis and also gave full protection to Alliance for Zero Extinction sites and Important Bird and Biodiversity Areas, which they assumed to be the equivalent of the 'areas of particular importance for biodiversity' mentioned in Aichi target 11 [1]. Butchart *et al.* [3] used human population density as a surrogate for costs. Pouzols *et al.* [7] prioritized areas for the conservation of the same species and ecosystems as Venter *et al.* [6] but valued each site using an additive species-specific benefit function, using a power function similar to the well-known species–area curve. This varies the marginal contribution of each site selected for conservation in a sigmoid fashion depending on the amount already protected. Pouzols *et al.* [7] also accounted for future habitat loss by comparing the prioritization done with current species ranges and with ranges whose contribution to the benefit function was discounted based on the expected future land-use change in these areas by 2040. This equates to assuming that future PAs cannot stem habitat loss and will be placed in land that is residual to future agricultural expansion. Under these circumstances, the global protection target should increase from 17% to 21% to achieve the level of protection needed under current land-use because of discounted contribution of areas subject to habitat conversion, and lost opportunities for efficient conservation.

These studies have been useful for identifying the most efficient networks of sites that contain under-protected species and ecosystems. However, none of them estimated or sought to maximize the impact of these PAs in reducing biodiversity loss, i.e. they did not investigate how the proposed PAs would reduce habitat loss under future scenarios of anthropogenic threats. Therefore, there is no evidence that these proposed PA expansion plans would improve the prognosis for these species, despite this being the ultimate goal of Aichi target 12, which commits countries to ensure that 'by 2020 the conservation status of known threatened species is improved and sustained' [1].

In addition, none of these studies attempted to estimate the potential conflicts between setting aside land for conservation and alternative human uses such as agriculture or agro-forestry. Dobrovolski *et al.* [8] quantified the amount of agricultural production that would be affected during the rest of the twenty-first century if the PAs were expanded to cover 17% of the world, with the goal of maximizing protection of terrestrial mammals. They found that the additional area selected for protection under this conservation scenario is expected to produce 27.6% of the twenty-first century total agricultural production in the absence of strict protection. Were this conservation plan implemented in the form of strict PAs, this agricultural production would have to be displaced somewhere else. The forgone agricultural production could be reduced to 6% if the projected agricultural opportunity cost of conservation were explicitly taken into account in the prioritization process. However, while more socio-economically viable, this conservation network would reduce the average coverage of terrestrial mammal species ranges by PAs from 64.3% to 43.1%. These results show that global conservation planning studies ignoring future socio-economic conditions, and in particular, expected agricultural production, give a false sense of feasibility based on the small amount of additional protection required to achieve all targets. Instead, it is possible that attempting to implement proposed conservation plans will imply a shortfall in land available for agriculture, resulting in negative effects for food security. Indeed the highest ecological impacts might well be achieved by setting aside areas with high agricultural opportunity costs [9].

Here we estimate the ecological and socio-economic impacts of two PA expansion plans aimed at achieving Aichi target 11 under two global socio-economic scenarios, a 'Business-as-usual' scenario, and an alternative scenario in which lifestyle changes are adopted that reduce *per capita* consumption of natural resources. We estimate the loss of native vegetation under each combination of the two socio-economic scenarios and two PA expansion plans aimed at achieving, respectively, representation targets for species and ecoregions. We then evaluate the ecological impact as the difference in extent of suitable habitat (ESH) for terrestrial mammals with and without additional protection. The net difference in suitable habitat for species with and without protection is a direct measure of contribution of PAs to achieving Aichi target 12, and it is the first time that this is estimated for any global PA expansion plan. We also evaluate the socio-economic impact of PAs as the shortfall in land required for meeting the demand for crops, timber and livestock projected by 2020, resulting from the constraints in human activities imposed by additional PAs.

2. Methods

(a) Protected area expansion by 2020

We carried out two analyses to assess the extent of land requiring conservation (in addition to existing PAs) to achieve the following targets, referred to respectively as 'ecoregion' targets and 'threatened species' targets: the 'ecoregion targets' required protecting 17% of the global terrestrial realm plus country-specific area coverage targets set by national governments as part of their CBD commitments (all of them $\geq$17%) plus 17% coverage of each of the 827 terrestrial ecoregions (ignoring country boundaries) as defined by the World Wildlife Fund [10]. The threatened species targets included targets for all threatened amphibians, birds and mammals for which range maps were available. We excluded Antarctica from our analyses owing to the absence of terrestrial mammals and amphibians, and the absence of land-use change.

These two analyses represent different interpretations of the CBD target 11 [1,3,6]. Except for the country-specific area coverage targets, both sets of targets are 'globalized' in the sense that they were achieved without considering national borders. The set of ecoregion targets is easier to achieve as it imposes fewer constraints on where protection should occur, but it is also less likely to provide benefits for species conservation because areas important for species conservation are not homogeneously distributed within ecoregions, so ecoregions are not good surrogates for species conservation [11]. The species targets are explicitly aimed at protecting threatened species, thereby contributing to the achievement of Aichi target 12 as well as Aichi target 11 [3,6].

To identify the PA expansion plans for threatened species conservation we first set representation targets for all threatened amphibians, birds and terrestrial mammals of the world for which range maps were available (4217 species, electronic supplementary material, table S5). These targets were set following Rodrigues *et al.* [12] and replicate the analyses performed by Butchart *et al.* [3] and Venter *et al.* [6]. This involved scaling proportional representation of species ranges in PAs by species' range sizes. Species with ranges $< 1000\ \mathrm{km}^2$ had a proportional target of 100% of range protected, whereas species with ranges $> 250\,000\ \mathrm{km}^2$ had a proportional target of 10%. We interpolated the proportional target on a log-linear scale between these two thresholds. We capped the area to be protected at 1 million km^2 for species with extremely large ranges (more than 10 million km^2), because landscape-scale conservation through sectoral policy interventions, such as agri-environmental schemes, is generally more appropriate for such species [13]. This cap affected nine bird and four mammal species. For the 115 migratory bird species in the dataset, the representation target was applied to both breeding and non-breeding ranges. When assessing PA coverage, the target was treated as having been met if coverage was greater than or equal to 99% of the target area.

To identify the additional areas requiring protection to meet the two sets of targets, we replicated the analyses of Butchart *et al.* [3]. We divided the world into 30 × 30 km grid cells, which constituted our 150 700 planning units. Within each of these, we calculated the area of each 'conservation feature' (species, ecoregion and country) as well as the fraction of each feature range already protected. We identified the additional areas to be protected to achieve all ecoregion and threatened species targets at the minimum cost with the Marxan software [14]. We used human population size in the planning units as a surrogate for the opportunity cost and difficulty of establishing PAs, so that heavily populated planning units were avoided unless they were needed for target attainment. This strategy of avoiding populated areas reflects current patterns in PA placement: the global average population density inside PAs is 20 people km^{-2} and the global overall average is 50 people km^{-2}, when both densities are calculated excluding Antarctica. We used the 1 km resolution Gridded Population of the World (GPWv3) dataset [15] in ArcGIS to calculate for each planning unit the total human population size, and the human population size within existing and proposed PAs. Estimates of future population density data for the socio-economic scenarios were not available, so we used current population density data.

While opportunity costs of conservation derived from agricultural rental are often used to minimize socio-economic costs of conservation [6,16,17], we opted against their use as they are poorly correlated with the prices for which lands are acquired for conservation [18]. Further, even accurate estimates of monetary opportunity costs are not always indicative of the socio-economic costs to local populations, for instance in areas where the main activity is subsistence farming [19].

All PA polygons were dissolved into a single planning unit that was set as automatically selected in Marxan [14], so that the software would identify additional planning units—entire or partial 30 × 30 km grid cells cut around existing PAs—that met the specified targets by complementing the existing PA network.

For each PA expansion plan (ecoregions and threatened species), we ran Marxan 100 times, each with 100 million iterations. Given the size of the grid cells (900 km^2), we did not attempt to impose spatial compactness to the proposed PA network, as individual proposed PAs would be sufficiently large to host a viable population of most species, and the aggregation would result naturally from the spatial autocorrelation in species distributions and human population density (figure 1). We identified which of the 100 PA portfolios had the lowest cost and used that portfolio as the 2020 PA coverage under each plan. From these, we removed all non-natural land-cover, to follow the assumption of previous studies that non-native vegetation should be ignored in identifying areas for conservation and achieving representation targets.

(b) Socio-economic scenarios

We used two socio-economic scenarios created to explore the implications of Business-as-usual and alternative socio-economic pathways for the achievement of the Sustainable Development Goals, agreed by the United Nations in 2015 and that aim to end poverty and hunger, ensure equality of gender, race and religion, and promote sustainable use of natural resources [20]. The quantitative assumptions on production and consumption patterns, and other technological and socio-economic parameters for each scenario, are in the electronic supplementary material, table S1. Regional area demand for different land-uses by 2020 for these scenarios are in electronic supplementary material, tables S3 and S4. These scenarios were developed until 2050, but here we only use their outputs until 2020, to evaluate the implications of these socio-economic changes on the achievement of the Aichi targets. Below (§2b(i,ii)) we describe the scenario storylines, and in the following section (§2c), we describe how we obtained the spatially explicit land-use scenarios associated with each of them.

(i) Business-as-usual

This scenario assumes that the trend towards modernization according to the western model continues, albeit with regional specificities. The basic socio-economic mechanisms continue to operate in the same fashion and no explicit new policies are introduced to meet sustainability goals. Economically, development is guided by the paradigm of maximizing productivity and efficiency through competition, innovation and the abolition of trade barriers. This scenario is not a prediction or forecast, but serves as a point of reference against which possible alternative future scenarios are evaluated.

(ii) Consumption change

This scenario is aimed at achieving development goals that include eradicating hunger and poverty by providing sustainable and equitable access to all basic resources, including food, water and energy, while safeguarding species and healthy ecosystems (electronic supplementary material, table S2). In this scenario, the world population becomes increasingly aware of environmental degradation and the lack of progress made in reducing global poverty in major parts of the world during the first decade of the twenty-first century. Consumers are prepared to change some of their consumption patterns. People realize that their search for the lowest cost and highest returns gives them private gain as consumers and investors but collective loss as global citizens. Citizens start to develop innovative customer and business models to resolve these tensions as they become better informed. In the food sector, a shift towards vegetarian diets occurs. This shift is driven not only by health concerns about meat consumption (cardiovascular disease, pandemics) and other effects of 'cheap food' (diabetes, obesity), but also by the fact that people become more aware of the indirect systemic consequences of the large-scale industrial food system. Another change is a reduced growth in personal travel and freight transport stimulated by more convenient infrastructures for other modes of transport (bicycle and public transport).

(c) Integrated model to assess the global environment (IMAGE)

We simulated spatially explicit socio-economic and biophysical changes for each scenario storyline with IMAGE, a comprehensive integrated modelling framework of interacting human and natural systems [21]. The human system comprises models of energy use, conversion and supply, and models of agricultural and forestry activities, affecting land-cover and land-use. Our implementation of IMAGE divides the world into 25 regions (electronic supplementary material, figure S1), each of which has specific socio-economic parameters, including the amount of extraction of natural resources and the production and consumption of primary goods such as food, timber, fossil fuels and energy.

In IMAGE, the spatial allocation of crops, pasture and bioenergy is driven by regional crop and grassland production and their respective intensity levels, as calculated by its agro-economic model, the potential crop and grass yields, and

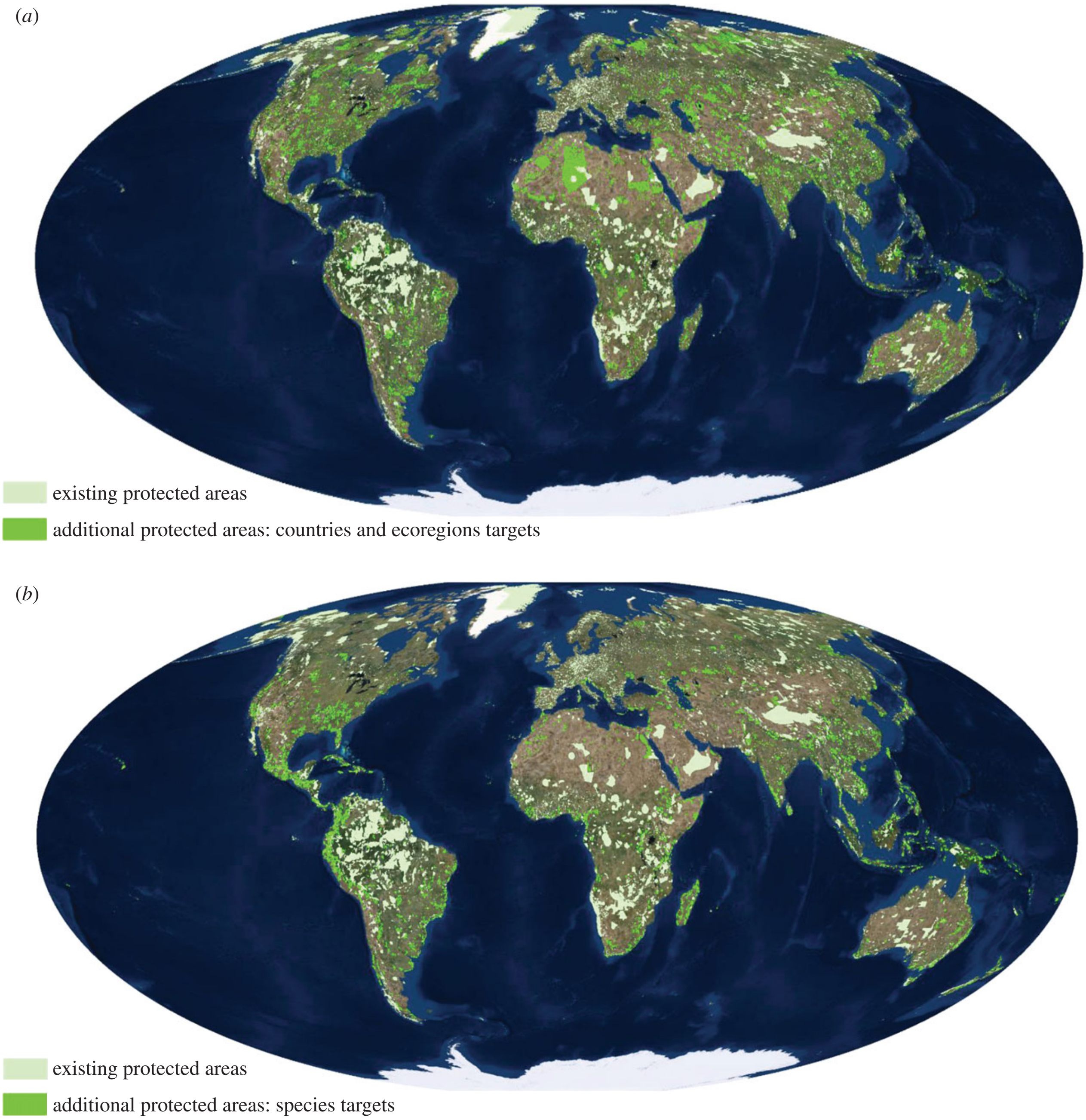

Figure 1. Existing and additional protected areas required to satisfy global targets for countries and terrestrial ecoregions (*a*), and for threatened amphibians, birds and mammals (*b*).

landscape suitability factors (e.g. growth seasons, water availability, etc.). Specifically, a sub-component of the system, GLOBIO, determines the location of agricultural expansion or abandonment, at a 6′ resolution. Agricultural land is expanded according to a suitability ranking (see [21], and supplementary information of [22]). The land-use classification system was a modification of the 23 classes of the Global Land Cover 2000 [23], which included grazing areas and sub-classes related to the type and intensity of agriculture and forestry, yielding a total of 66 classes [24].

We assumed that all future PAs are immune to agricultural expansion (equivalent to PAs in International Union for Conservation of Nature (IUCN) category I–IV, currently accounting for 75% of all terrestrial PAs for which management category is known). We applied this assumption for the PA expansion plans identified for both sets of objectives, based on the interpretation of Aichi target 11 as aimed at species and ecosystem conservation. The same assumption was implicitly made also in all other recent studies [3,6,25], with the exception of Pouzols *et al.* [7]. Below, we explore the implications of this assumption when assessing future food security. We also assumed that existing PAs will maintain their current mix of land-uses until 2020. This assumption is justified by the fact that 25% of all existing terrestrial PAs are under IUCN management categories V–VI, for which sustainable use of natural resources, including farming, grazing and timber harvesting is allowed. Therefore, we assume that all PAs subject to human uses fall into these management categories and will maintain their current use to promote human livelihoods and cultural landscapes.

(d) Ecological impact of socio-economic and conservation scenarios

We assessed the impacts of different socio-economic scenarios coupled with different PA expansion plans on the ESH for 5145 species of terrestrial mammals, globally (97% of all mammal species). We therefore assessed impacts using ESH for mammals, while we planned PA expansion for threatened mammals, birds and amphibians. The reasons for this mixed approach

Table 1. Summary results of ecological and socio-economic impacts of the combination of two socio-economic scenarios and two protected-area expansion plans. Ecological impact is measured as the median value across all species of $ESH_{s,x}/ESH_{s,c}$, that is, the ratio between the extent of suitable habitat projected for a species under a given combination of scenario and conservation plan in 2020, and the extent of suitable habitat projected for that species under business as usual and in absence of further protection. BAU, Business-as-usual scenario; CC, Consumption Change scenario; eco, protected area expansion plan for ecoregions (which included targets for ecoregions, country commitments to CBD, and a global target of 17% of land); sp, protected area expansion plan for species.

	land protected (%)	population density (people km^{-2}) inside PAs (outside PAs)	median ecological impact (dimensionless)	unmet demand cropland (km^2)	unmet demand pastures (km^2)	unmet demand forestry (km^2)
BAU.eco	18	29.1 (51.3)	1.007	63 803	131 049	122 393
BAU.sp	17	96.8 (47.7)	1.017	60 240	124 304	127 202
CC.eco	18	29.1 (51.3)	1.012	76 566	95 895	124 235
CC.sp	17	96.8 (47.7)	1.048	75 508	81 850	126 773

were the lack of ESH for taxa other than mammals and the greater reliability of ESH for our purposes.

ESH is a better proxy for the conservation status of a species than range size, as the latter typically contains extensive areas that are unsuitable or not occupied by the species. Terrestrial mammals are the only taxonomic group for which ESH can be estimated globally with published models [26]. The extent of native vegetation retained within a species range, while applicable to all taxonomic groups, would be a misleading measure of PA impact. Habitat loss is almost never randomly distributed throughout a species range because agricultural suitability is often extremely variable throughout it. Therefore, changes in natural vegetation within a species range typically do not appropriately reflect changes in suitable habitat for the same species, thus potentially giving misleading results. On the contrary, the proportion of ESH remaining is an unbiased estimator of the impact of land-use change within a species range. However, a conservation plan established for mammals only would be unrealistic, as conservation agencies typically consider several taxonomic groups when identifying candidate PAs, especially other vertebrates and plants, thus we decided to establish priorities for the conservation of all terrestrial vertebrate taxa for which we had comprehensive range maps, while evaluating PAs' impact using ESH models for mammals, the only group for which they are publicly available.

We used the IUCN Global Mammal Assessment habitat suitability models (classifying a given land-cover and land-use type as either suitable or not [22,26]) to quantify the ESH (km^2) within a species' geographical range, obtained from the IUCN Red List dataset [27]. We assessed the ESH change within each species' range owing to land-use change by 2020. A description of the habitat suitability models is in the electronic supplementary material.

For each species s and for each combination of socio-economic scenario and PA expansion plan (conservation scenario) x, we measured the conservation impact as $I_{s,x} = ESH_{s,x}/ESH_{s,c}$ where the numerator is the ESH for species s under conservation scenario x and the denominator is the ESH under the counterfactual conservation scenario resulting from the Business-as-usual socio-economic scenario and no additional protection. We report summary statistics for all species, for groups of species in different quartiles of the range-size distribution, and for threatened species according to the IUCN classification (categories Vulnerable, Endangered and Critically Endangered) [28].

(e) Socio-economic impact of conservation scenarios

For each conservation scenario and each of the 25 economic macro-regions of the world (electronic supplementary material, figure S1), we calculated the difference between the area needed to meet regional and global demands for agricultural products and timber under each socio-economic scenario, and the area that was possible to allocate to these land-uses based on land suitability and existing and future PA constraints. We call these quantities area shortfalls; any regional shortfall implies a risk of food-insecurity. We investigated whether conservation efforts that led to increased ecological impacts also led to increase in socio-economic impacts using zero-inflated mixed-effect Poisson models, with shortfall in areas dedicated to production of each commodity as a response variable, the geometric mean of the ecological impact as a fixed effect, and the macro-region as a random effect.

3. Results

Achieving ecoregion targets required an additional 6.8 million km^2 of PAs globally, so the total PA network had an area of 26.5 million km^2 and covered 18% of the world land mass (19.6% excluding Antarctica). These additional PAs were distributed fairly homogeneously across the planet (figure 1*a*). Achieving species-specific representation targets for terrestrial vertebrates required an additional 5.32 million km^2 of PAs globally, which, in addition to current PAs, covered 17% of the world (18.5% excluding Antarctica). These tended to be in biodiversity hotspots, e.g. the Andes, Madagascar, the Western Ghats, Eastern Himalayas and Mesoamerica [29] (figure 1*b*).

All ecoregion and threatened species targets could be met. However, the PA impacts greatly depended on the conservation targets and the socio-economic scenarios in which these were established (see §3(b–d)). Table 1 summarizes all ecological and socio-economic impacts across all conservation plan and socio-economic scenarios combinations.

(a) Counterfactual outcomes

In the absence of additional protection, and under Business-as-usual socio-economic policies and demographic and technological trends, on average, the ESH for terrestrial mammals was expected to decline by 9% from 2010 to 2020. Under the Consumption Change scenario, the ESH was expected to increase by 2%. For threatened terrestrial mammals these statistics were, respectively, −6% and +2%.

(b) Protected area impact under the Business-as-usual socio-economic scenario

(i) Targets for ecoregions

A global PA network expanded to achieve the ecoregion targets provided less than 1% additional suitable habitat in 2020

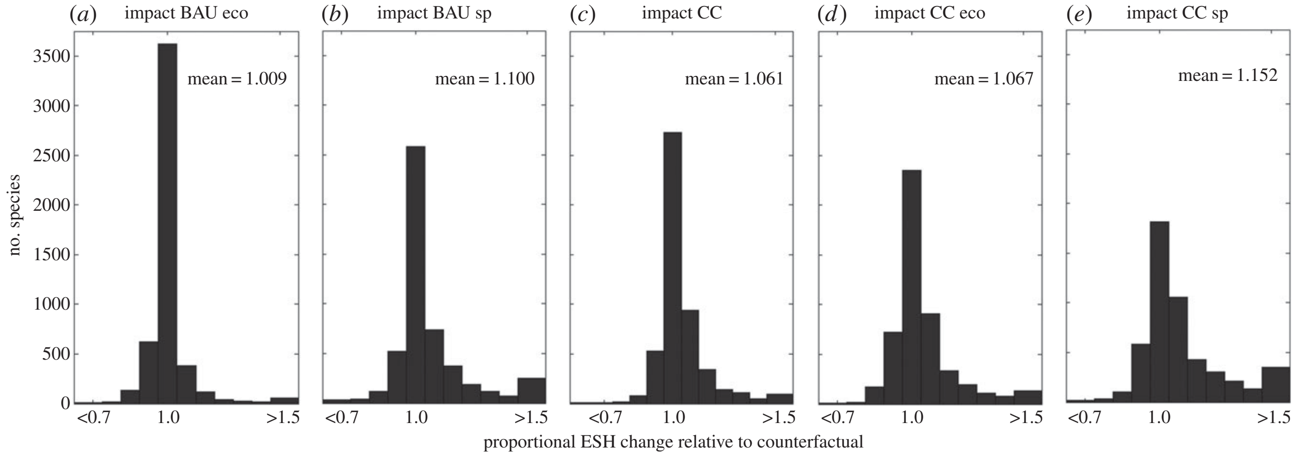

Figure 2. Ecological impact on terrestrial mammal species of existing and proposed protected areas and lifestyle changes by 2020. Definitions and scenario labels as in table 1. (Online version in colour.)

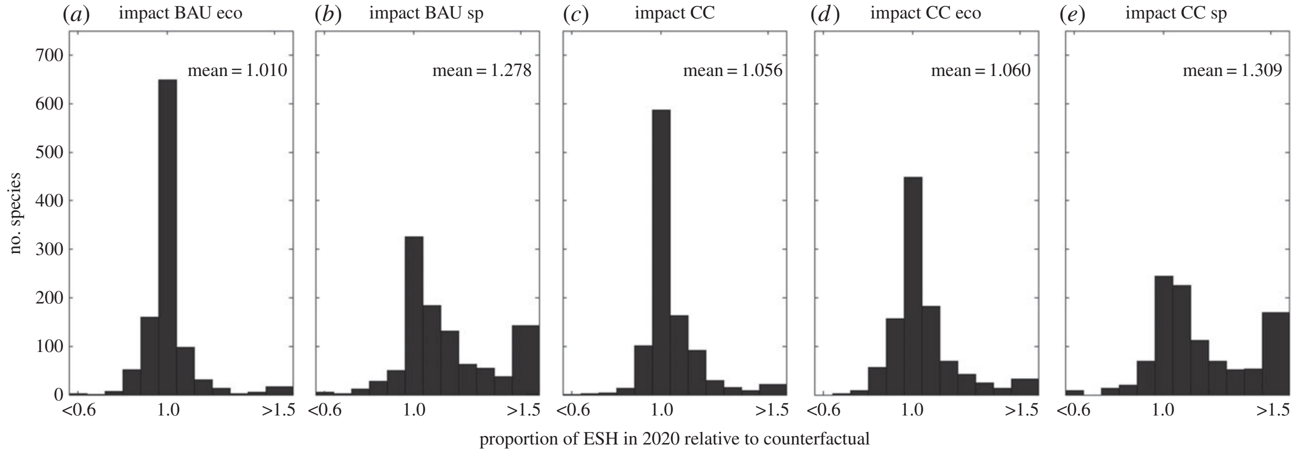

Figure 3. Ecological impact on threatened terrestrial mammal species of existing and proposed protected areas and lifestyle changes by 2020. Definitions and scenario labels as in table 1. (Online version in colour.)

on average for all terrestrial mammal species, in comparison to the counterfactual outcome (figure 2*a*). Implementing this PA expansion plan could even have negative effects for species conservation. In fact, 58.4% of the terrestrial mammal species were projected to incur a relative loss in suitable habitat with respect to the counterfactual outcome. The number of species with negative impacts increased to 59.7% when considering threatened mammals only (figure 3*a*).

By minimizing human population density within additional PAs subject to the constraint of achieving ecoregion and country targets, this PA expansion plan incidentally avoided protecting the areas richest in threatened species. In fact, the units selected for protection under this strategy host on average 2.78 threatened mammal species versus 2.83 in the units left unprotected. These averages are, respectively, 6.52 and 6.86 species per unit protected when considering threatened species across all taxonomic groups prioritized for which we had range maps (amphibians, birds and mammals).

When stratifying the results across range-size classes, we found that, for all strata, the mean impact was positive. However, more than half of the species in the first three quartiles of range-size classes had negative impacts (figure 4). The species in the top 25% of range-size distribution were the only exception in that the majority of species in this class were estimated to benefit from the achievement of ecoregion targets (figure 4*p*,*s*).

(ii) Targets for threatened species

The global PA network expanded to adequately protect threatened species increased the ESH of terrestrial mammals relative to the counterfactual of no additional protection for 61% of the species in this group; the average increase was 10% (figure 2*b*). PA impact was positive for 79.2% of threatened mammals, and the average improvement relative to the counterfactuals was 27.8% for species in this group (figure 3*b*).

(c) Protected area impact under the Consumption Change socio-economic scenario

(i) Targets for ecoregions

Achieving ecoregion targets under the Consumption Change scenario increased the ESH available to 60% of terrestrial mammals with respect to the counterfactual outcome (figure 2*d*); the average increase was 6.7%. When considering

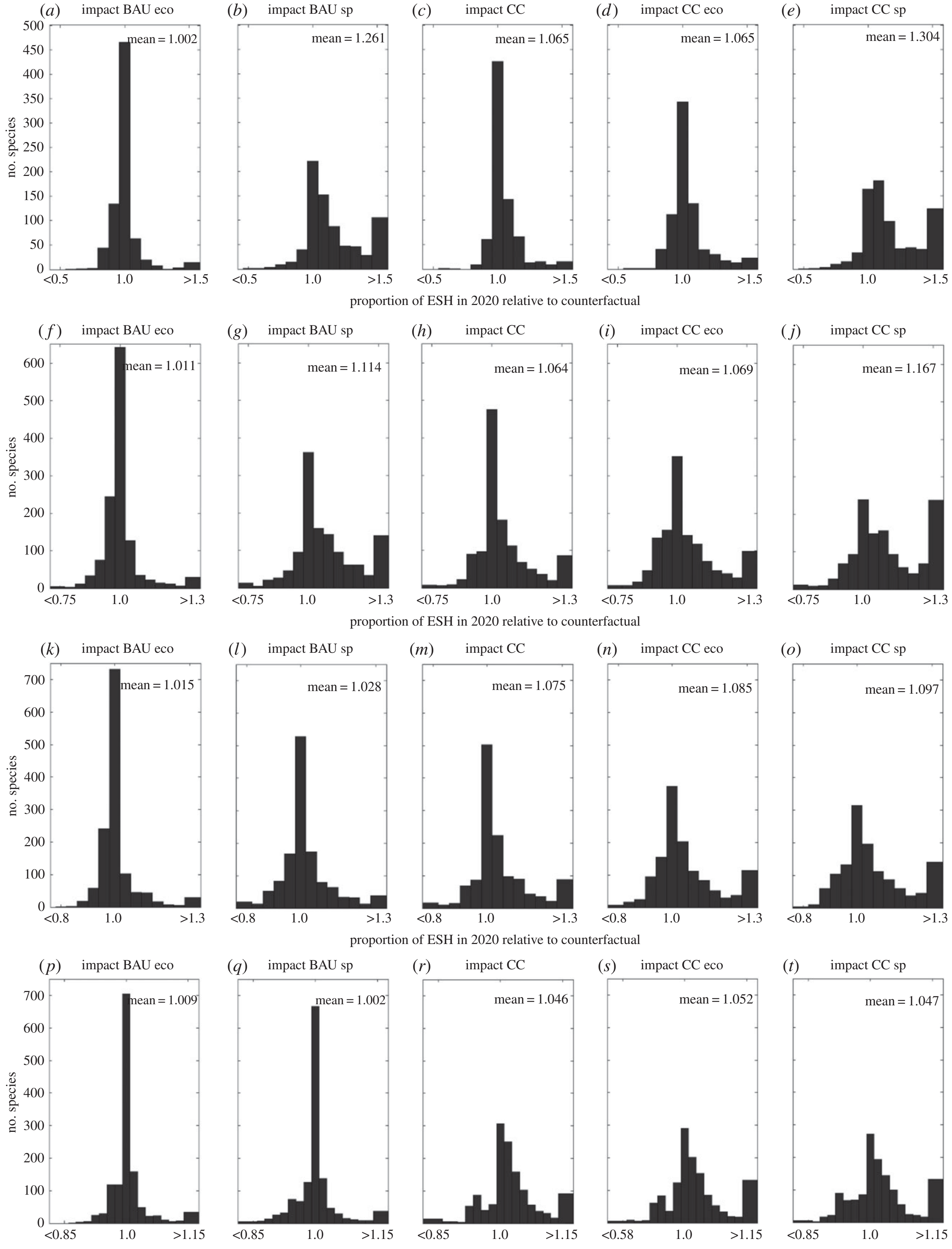

Figure 4. Ecological impact of existing and proposed protected areas and lifestyle changes by 2020 on terrestrial mammal species of different range-size classes. (*a–e*) Species in the first quartile in mammal range size, (*f–j*) species in the second quartile, (*k–o*) species in the third quartile, (*p–t*) species in the last quartile. Definitions and scenario labels as in table 1. (Online version in colour.)

only threatened terrestrial mammals, 57.5% benefited from this PA network and the average increase was 6.1% (figure 3*d*). These results are very similar to the conservation scenario Consumption Change without additional protection (figures 2*c* and 3*c*), which implies that nearly all impact can be attributed to changes in lifestyle and more sustainable production rather than additional PAs. This combination of conservation actions and consumption changes has the highest conservation impact relative to other combinations for species in the top quartile of range size (figure 4*s*).

(ii) Targets for threatened species

Expanding PAs globally to target the conservation of threatened terrestrial vertebrates, under the Consumption Change scenario, increased the ESH available to 71% of terrestrial mammals and on average by 15.2% relative to the counterfactual of no additional protection and no changes in lifestyle (figure 2*e*). When considering threatened mammals only, 80.6% of the species were positively affected and the mean improvement on the counterfactual was 30.9%, i.e. on average the ESH of threatened terrestrial mammals would be one-third larger in this scenario than if no additional protection and lifestyle changes occurred by 2020 (figure 3*e*). Similar to the BAU scenario, the highest impacts were found for range-restricted species (the quartile of species with smallest ranges), which had an average 30.4% increase in ESH by 2020 relative to the counterfactual (figure 4*d*).

(d) Socio-economic effects of conservation scenarios

(i) Human population density in protected areas

The population density inside areas earmarked for additional protection under the PA expansion plan for ecoregions was 29.1 people km^{-2} and outside was 51.3 people km^{-2}. The human density inside additional areas earmarked for protection for threatened species targets was 96.8 people km^{-2} and outside was 47.7 people km^{-2}. These values were the same under both socio-economic scenarios because we used current population density to obtain them.

(ii) Unmet demand for cropland, pastures and forestry areas

The PA expansion plan for ecoregions generated a shortfall in availability of agricultural land (cropland and pastures) in Northern Africa and in the Middle East (electronic supplementary material, table S5). These conflicts between conservation and agriculture were somewhat reduced in the Consumption Change scenario. We also found a shortfall in the amount of forest subject to clear-cut and selective logging in 2020 for the BAU and Consumption Change scenarios in two regions: Indonesia + Papua New Guinea (PNG) and Central Asia. For both regions, the total shortfall in area subject to periodic harvest was slightly lower in BAU with respect to Consumption Change because part of the timber is obtained from deforestation followed by plantation of intensive crops which, for these regions, is higher in the BAU scenario than in Consumption Change scenario. In addition, in the Consumption Change scenario, the amount of cropland area projected by 2020 is slightly higher in Africa and parts of Asia, in order to meet the goal of achieving global food security (electronic supplementary material, table S4 and [30]).

When targeting PA expansion to protect threatened species, under the BAU scenario there were shortfalls in agricultural land in Northern Africa, Middle East and Central America except Mexico (electronic supplementary material, table S6). Under the Consumption Change scenario a shortfall remains only for Northern Africa, and is reduced there. There are also comparable shortfalls in area subject to forest harvest in Indonesia + PNG and Central Asia.

Socio-economic impacts (total shortfall in area dedicated to human land-use in a region) and ecological impacts (geometric mean of ratio of ESH with and without PAs) were not correlated with each other under any conservation target, socio-economic scenario or type of commodity considered (all *p*-values of regression coefficients of ecological impact as a predictor of socio-economic impact where $\gg 0.1$).

4. Discussion

We estimated the expected future impacts on species and human activities of alternative proposals for achieving Aichi target 11. When interpreting this target as aimed at representing ecoregions and meeting national commitments to PA expansion, under a Business-as-usual socio-economic scenario, we found that more than 50% of terrestrial mammal species in 2020 will have lost more habitat within their range than if no additional PAs were implemented. This is because PAs designed to achieve ecoregion targets while avoiding highly populated areas displace future agricultural land towards low-lying, more densely populated but species-rich areas. This is essentially a backward step for conservation, perpetuating the tendency of protecting the ‘land nobody wants’, leaving imperiled species at risk from habitat loss [31].

Interpreting Aichi target 11 as specifically aimed at protecting threatened and range-restricted species, and assuming that PAs are effectively enforced and immune to habitat loss, are expected to have positive effects on these species. PA expansion driven by this interpretation of Aichi target 11 can therefore contribute to the achievement of Aichi target 12, as we show here. However, PAs are not the appropriate tool for protecting wide-ranging species [13], and in fact, these species were projected to decline even if granted additional protection under the BAU socio-economic scenario. Through our analyses of projected land-use change under the Consumption Change scenario, we found that changes in consumption patterns will have larger impacts than expanding PAs for terrestrial mammal species in the upper half of the range-size distribution.

We found that protecting threatened species will imply setting aside land for conservation in densely populated areas, even when explicitly attempting to avoid them during the conservation prioritization process. This means that countries and conservation agencies willing to adopt proposals for targeted protection of threatened species, in areas such as those identified by Venter *et al.* [6] and Butchart *et al.* [3], will face higher challenges than at present in ensuring legal enforcement of protected status, unless socio-economic changes are put in place to ‘make space for conservation’. In fact, assuming that these PAs will be dedicated to species and ecosystem conservation (IUCN protected area categories I–IV) implies that habitat conversion will be prohibited. We found that this could create a future shortfall in crops, livestock and timber in different parts of the world under both socio-economic scenarios tested here, and particularly under Business-as-usual socio-economic trends. Decision-makers may decide not to incur these opportunity costs of conservation by adopting ecoregional or other more flexible targets, with substantial negative repercussions for species, as we show here. Importantly, we found that there was no correlation between ecological and socio-economic impact; that is, improving on the counterfactual ecological impact did not increase the likelihood of running out of space for agriculture or forestry in a region. This is probably because the areas with the highest positive ecological impact of PA expansion plans for threatened species will meet their agricultural demand through agriculture intensification (e.g. Indonesia, India), rather than through clearing native vegetation.

Our study highlights that conservation planning cannot be done without considering the socio-economic context in which the proposed conservation interventions will take place. This requires integrating spatial conservation prioritization methods with agricultural economic models and land-use change models. Here we have provided for the first time a soft integration of them, by adjusting future land supply based on proposed PAs and simulating agricultural expansion under alternative socio-economic scenarios. This has allowed us to estimate the future ecological and socio-economic impacts of proposed PAs, which include potential trade-offs between biodiversity conservation and food security. This has also allowed us to make spatially explicit scenarios of leakage of habitat loss, outside PAs, owing to their displacement effects on land-conversion, and quantify the impact of this displacement effect on terrestrial mammals.

In order to fully integrate and harmonize conservation plans into socio-economic development scenarios, beyond the soft integration here, we suggest that conservation tactics to mitigate or displace threats to species, such as PAs, and policy strategies to reduce these threats, be generated together. This can be done by using back-casting techniques, in which the policy scenarios are the output of the modelling and simulation process, rather than the input as in forecasts. Back-casting socio-economic scenarios starts with defining desirable future conditions (e.g. a prescribed spatial distribution of natural vegetation such that all species are extant and viable in 2100) and walks backwards to the present day through sequential optimization of general equilibrium economic models. This dynamic integration will promote coherent and integrated planning of local-scale conservation interventions and large-scale economic and environmental policies.

Authors' contributions. P.V. conceived the idea, designed the study, coded the habitat suitability models, ran the Marxan analyses, calculated the ecological impacts of PAs, analysed all the results and wrote the manuscript. M.B. ran the IMAGE-GLOBIO model to obtain the land-use change maps and the shortfall in commodities under all conservation scenarios. R.J.S. and R.E.S. produced the Marxan input files and provided other spatial datasets. All authors read and helped draft the manuscript and gave final approval for publication.

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