Title: Integrated spatial planning for biodiversity conservation and food production

Authors: Fastré, C. [1,2*], van Zeist, W-J.[3], Watson, J.E.M.[4] and Visconti, P.[5]*

Affiliations:
[1] Institute of Zoology, Zoological Society of London, London NW1 4RY, UK
[2] Antwerp University, Universiteitsplein, 1, Wilrijk, Belgium
[3] PBL Netherlands Environmental Assessment Agency, Den Haag, The Netherlands
[4] Centre for Biodiversity and Conservation, University of Queensland, Brisbane, Australia
[5] IIASA International Institute for Applied Systems Analysis, Vienna, Austria
***Corresponding authors: visconti@iiasa.ac.at, constancefastre@gmail.com**

Lead contact: Visconti P.

Summary

Ambitious area-based conservation targets are at the forefront of the post-2020 biodiversity conservation agenda[1,2]. However, implementing such targets cannot be done without accounting for the increasing demand for farmland products[2–4], the main driver of biodiversity loss worldwide[5,6]. Here we analyse the expected conservation gains and farming opportunity costs of three alternative global conservation strategies under business-as-usual demand in farmland products by 2030. We find that integrated spatial planning can reach the same species conservation objectives at 25-40% of the opportunity cost for food production, or 400-600% the biodiversity benefit for similar opportunity costs than planning for each objective separately. This requires managing over 60% of land in ways that are compatible with biodiversity conservation, which includes restoring 8%-11% of land surface. Achieving global conservation targets can be compatible with protecting biodiversity and ensuring food security but only with efforts to negotiate land governance strategies across multiple stakeholders and their objectives.

Introduction

The Convention on Biological Diversity (CBD) "Aichi" Target 11 established a global commitment to protect an ecologically representative, well connected, effectively and equitably managed 17% of land and 10% of the oceans by 2020[7]. While the areal component of Target 11 has been almost achieved, very limited progress has been made on the qualitative elements of this target[7–10], and this has contributed to the limited progress to achieving other targets, chiefly, the conservation of threatened species (Aichi Target 12)[7,10]. To address the shortcomings of the 2020 protected area target, policy proposals have emerged that suggest adopting targets that are based on outcomes (e.g. species persistence) rather than percentage area coverage[11]. Proposals advocating for larger percentage area targets have also emerged[2,12,13], with one in particular calling for the protection or restoration of 30% of land and oceans by 2030, focusing on areas considered to be of high importance for biodiversity[14] and another 20% to be managed sustainably as Climate Stabilization Areas for their potential and realized contribution to carbon storage, as interim targets towards protecting Half Earth[15,16].

The acceptance of a bolder area-based conservation agenda at the 15th CBD COP[3,14,19,20,37] is possible with the present post-2020 Global Biodiversity Framework (GBF) proposing 2 ambitious action targets: Target 1) "Ensure that all land and sea areas globally are under integrated biodiversity-inclusive spatial planning addressing land- and sea-use change, retaining existing intact and wilderness areas" and Target 3) "Ensure that at least 30 per cent globally of land areas and of sea areas, especially areas of particular importance for biodiversity and its contributions to people, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes".

However, the protection large proportion of the planet would likely result in land use conflicts with other land uses such as croplands and pastures and could potentially impact global food production and local livelihoods[3,17,18]. It is therefore crucial that assessments of area-based proposals are undertaken in terms of their socio-economic implications, especially for farmland production[3,4], and their potential to conserve biodiversity[11,19].

Recent studies have assessed the implications of taking extreme assumptions with regards to setting aside half the terrestrial planet for conservation in terms of food production shortfalls[3] and number of people affected[21], finding that depending on how conservation areas are prioritized, up to 1 billion people could be affected, in ways that depend on the local context and the specific governance and management of these areas [21] and 15–31% of cropland and 10–45% of pasture could also be compromised[3]. Other studies identified ways to meet global demand for food and fibre through transformational socio-economic and technological changes and trade optimization[18,22,23].

However, to date, no attempt has been made to resolve trade-offs between food production and implementing alternative proposals for protecting 30% of land by 2030, nor have these proposals been tested in terms of their contribution to improving species conservation status, one of the key targets of the CBD and of the Sustainable Development Targets (SDGs)[2,4,24]. The feasibility and efficiency of setting aside 30% of land for conservation therefore remains untested, with few months remaining before parties to the Convention on Biological Diversity agree on the post-2020 Global Biodiversity Framework[1].

Here we simulate three alternative conservation strategies to estimate how much of Earth's land surface should be managed to minimize the extinction risk of 4323 terrestrial mammal and 8541 bird species for which distribution ranges and habitat preferences were available

(79% and 85% of known mammal and bird species, respectively) while achieving global farmland production demand.

Unlike previous studies that designed or tested area-based conservation measures using representation targets[25,26], we define sufficiency of a network of conserved areas utilising methodologies from extinction risk analyses[27,28], thereby effectively designing a network of conservation areas that contribute to species persistence. In addition, rather than assigning areas to a simplistic binary status of ‘protected or not’, we zone the planet into land-use and land-cover classes, which allows us to mimic the implementation of the GBF Target 1, through integrated spatial planning for food production and species conservation at the same time. Additionally, this approach goes beyond the ubiquitous assumption that species conservation can be achieved only within protected areas embraces the notion that conservation targets can be achieved through ‘Other Effective area-based Conserved Measures’ or ‘OECM’ [29].

We found that integrated land-use planning for food production and biodiversity has the potential to minimize trade-offs between these competing uses of land. If applied across all countries and ecosystems it means only 2.7% of mammal and 1.2% of bird species could be left at risk of extinction (currently there are over -26% of terrestrial mammals and -13% of terrestrial birds at risk of extinction[30]) while resulting in minimal food production shortfalls under business-as-usual demand and supply of agricultural products: (3.6% of global pasturelands and 1.2% of global food crop production).

We must note that land-use change is only one of the threatening processes affecting species globally; in order for species conservation targets to be achieved in natural and restored areas, managing other threatening processes such as climate change, direct harvesting and invasive species is clearly necessary[22,31]. As such, when we refer to conservation management throughout this paper we mean management that specifically addresses all local threats to biodiversity, including those we do not specifically model spatially.

Results

Approach summary

We test action targets 1 and 3 of the proposed GBF in isolation and combination to derive 3 area-based conservation strategies (The Integrated Land Use Planning strategy (ILUP), the 30% strategy and the 30% + ILUP strategy, Box 1). These strategies are not intended to be actionable conservation plans, but rather an assessment of the potential ecological performance and socio-economic feasibility of proposed approaches to guide area-based conservation under the new GBF. We distinguish these strategies from scenarios, which are defined by global socio-economic, technological, and behavioural changes that are indirect drivers of environmental change. All strategies are applied under 1 global scenario, described below. Given the intrinsic uncertainties in future land-use change, we performed 50 replicates simulations of each strategy, each satisfying regional demand for agricultural products, but with different spatial configurations (see Experimental procedure for detail).

In the Integrated-Land-Use-Planning (ILUP) strategy, we spatially allocate habitat conservation and restoration of natural land-cover types and farmland (croplands and pastures) outside of the current Protected Area (PA) network to achieve species conservation targets and farmland production targets in 2030. Within the PA network, the present amount of different land-cover and land-use types is maintained constant in 2030. We call this strategy ILUP because it integrates both targets for species conservation and food production within a single multi-objective land-use planning exercise. This strategy therefore simulates the implementation of the action target 1 of the Global Biodiversity Framework (retaining and restoring terrestrial ecosystems by having at least 50% of land under spatial planning).

In the 30% strategy, we spatially allocate natural land cover types and farmland to achieve farmland production targets in 2030 under the constraint that ~30% of land, considered to be of global significance for biodiversity conservation (hereafter referred to as 'Biodiversity Areas', see Experimental procedure), is protected (i.e., locked out of farmland production). This strategy simulates a specific stringent possible implementation of the action target 3 of the draft GBF (protect and conserve at least 30 per cent of the planet with a focus on areas particularly important for biodiversity) in absence of action target 1. Farmland production targets are therefore met in areas residual to a pre-defined 30% of the world which is dedicated to biodiversity conservation.

In the 30%+ILUP strategy**,** we spatially allocate natural land cover types and farmland to achieve both species conservation and farmland production targets in 2030 under the constraint that the Biodiversity Areas are locked out of farmland production. This strategy therefore integrates the 30% protection in the Biodiversity Areas with integrated land-use planning for biodiversity and food security outside them, thereby simulating the implementation of action target 1 and a stringent version of target 3 of the GBF.

For all strategies, Land Use – Land Cover (LULC) allocation is subject to spatial constraints. First, farmland (croplands and pastures) are preferentially spatially allocated or relocated to areas suitable for farming activities and no further than 100 km from existing farmland. This satisfies at the same time realistic logistical constraints, as well as the aim of the post-2020 framework to retain "existing intact areas and wilderness"[1]. Second, the allocation of natural land cover types is constrained to intact habitats (habitats to be managed for species conservation) or areas within 10 km of where intact habitats remain (habitats to be restored), thereby accounting for both ecological suitability and likelihood of natural recolonization of animal and plant species in sites to be restored.

For each of the three conservation strategies, we explore the feasibility to achieve farmland production targets for pastureland and for food and biofuel crops, assuming the same projected Business-as-Usual (BAU) farmland production and consumption patterns to 2030.

Sufficiency of conservation strategies

Due to the modest variance in all performance metrics (<1%) across the 50 replicate simulations of each strategy, we report the results of the best performing replicate for each strategy. We find that, under the business-as-usual scenario of global food production and consumption, it is necessary to manage 61% to 64% of the Earth's surface to conserve species to bring the extinction risk to the lowest category for 96% and 97% of the mammal and bird species included in the analysis, while minimizing crop and pasture production shortfalls (i.e. the deficit of production amounts necessary to meet farmland production targets, Figure 1 and Figure S1 and 2). For the remaining species, the current range is too small to ensure that sufficient area of habitat is maintained or restored for the species to be classified in the lowest extinction risk category. These species would need to colonize, naturally or via assisted colonization, areas outside their current distribution. Across strategies, the proportion of land that should be managed for conservation is highest in North America (60-62% of the total surface), followed by Asia (55-56%, Figure S1d).

The ILUP strategy, unconstrained by the strict protection of Biodiversity Areas, thus allowing for most flexibility in spatially allocating natural land cover types and farmland, performed best, leaving 2.7% of mammal and 1.2% of bird species at risk of extinction and achieving the lowest food production shortfalls (3.6% of global pasturelands and 1.2% of global food crop production, Figure 1a and 2). In the ILUP strategy, 12% (5.2 million km²) and 17% (7.5 million km²) of the Biodiversity Areas are allocated to cropland and pastureland, respectively.

The 30% strategy, which focuses conservation efforts only in Biodiversity Areas and optimizes food production outside these areas, generates small food production shortfalls (5.8% of global pasturelands and 1.1% global food crop production) but results in 19.8% of mammals and 32.1% of birds being at high risk of extinction by 2030 (Fig. 1b and Fig. 2). These figures represent the opportunity cost of relying exclusively on protected areas rather than accounting conservation objectives within integrated spatial planning everywhere, as proposed by GBF Action Target 1.

The 30%+ILUP strategy, which as well as setting aside Biodiversity Areas for conservation, attempts to minimize trade-off between species conservation and food production outside them, gives the best biodiversity outcomes (3.9% of mammals and 3.8% of birds at risk of extinction) but is associated with the highest food production shortfalls (9.9% global needed pastureland and 4.3% global food crop production, Fig. 1c and Fig. 2). These food production shortfalls represent the opportunity cost of strict protection of a biodiversity rich ~30% of the planet and equates to 5% of the global food availability (including meat and milk production from pastures), more than three times the impact of both ILUP and 30% strategies (<2% decrease in global food availability).

To reach conservation targets across all the strategies, between 12 and 17 million km^2 of land must be restored, that is, re-zoned from anthropogenic land-use classes to natural ones; this is equivalent respectively to 7.6% and 11.0% of the land globally, excluding Antarctica (Figure S1). This amount is almost 4 times the global target of restoring 3.5 million km² by 2030 under the Bonn Challenge[22,23]. Habitat restoration is mostly needed in South America (14-16% of the total land), Europe (11%-22%) and Africa (6-10%). Although this would require an unprecedented, global habitat restoration effort, recent studies suggest this is both technically and socio-economically feasible[23,32].

Discussion

Implications for food production

Our results confirm that following current socio-economic trends, ambitious conservation targets, even if combined with careful planning, will likely impact food production[3]. Shortfalls in food production are most consistently found in different parts of Oceania, Africa, Central America, Middle East and Central Asia and these estimates are likely to be optimistic. Indeed, relocating farming activities within 100 km of current cropland and pastureland may be financially and logistically prohibitive and potentially affect hundreds of millions of people in rural areas, especially in developing countries[21]. Multiple ways to tackle food production problems however exist as the key determinants of future land-use include farmland intensification and changes in consumption patterns to reduce waste and reliance on resource-intensive food products[22].

Conserving biodiversity

Prioritizing the conservation of bird and mammal species in this analysis appears to be a good proxy for the representation of major ecosystem types. For example, the proposed target of ensuring that 30% of each ecoregion remains in a natural state[6] so as to maintain habitat diversity and ecosystem services, is achieved respectively for 83%, 91% and 94% of the world ecoregions with the ILUP, 30% and 30%+ILUP strategy (Figure S3). However, meeting demand for farmland products by 2030 results in the increase of farming activities (from 30% to an average of 33% of the global land across strategies) at the expense of global forested areas (from 31% down to an average 24% of the Earth’s surface covered by forests across strategies).

This may be problematic as additional loss of natural habitats, and especially forests, is predicted to intensify climate change effects and disrupt ecosystem services[14,33].

Due to the lack of available information on habitat affiliation, many other taxa (such as reptiles and plants) could not be explicitly included in the analysis. However, because their ranges (when available) were considered in the identification of the Biodiversity Areas, the areas identified as of conservation importance by the 30% and 30%+ILUP strategies should contribute to the conservation of these other taxa. Given the high overlap in priority areas across scenarios, and the good coverage of >80% of the world ecoregions, we expect the ILUP strategy to also contribute substantially to conservation of taxa other than birds and mammals as well as achieving targets for ecosystem integrity. We note, however, that accounting for plant distribution may change the local geography of conservation priorities[34] and should be considered in spatial planning.

Feasibility

Whether global conservation strategies such as those proposed here are likely to be implemented depends on many factors including the benefits and costs they can provide to society. Conservation strategies associated with smaller costs and allowing for more flexibility are more likely to be adopted. Our simulations show that implementing integrated land-use strategies (ILUP), in which both biodiversity conservation and agricultural production are considered, delivers better outcomes for biodiversity while minimizing food production shortages and the costs associated with restoring natural habitats compared to both strategies focusing on strictly protecting pre-defined biodiverse areas (30% strategies, Box 1). Unlike the 30% strategy, the ILUP strategy would require conservation efforts to be spread across the entire planet, instead of focusing on some areas only, meaning its implementation would require global actions and coordination and affect populations worldwide. While such a level of global commitment would be hard to secure, the benefits for people and biodiversity delivered by investing in planning would be highest on the long-term, making it more feasible than any of the other strategies tested here.

Future research to support real world implementation

We coupled target-based planning for biodiversity conservation and food production within a spatial optimization framework at the global level. While this is a theoretical exercise aimed at investigating the maximum potential for integrated spatial planning, this approach has been applied at the catchment level to inform real-world decidsion[35] and it is widespread in marine and coastal areas with about 70 countries now having marine spatial plans which include multi-objective zoning[36]. This approach has been also advocated by scientists and conservation practitioners, and dubbed a "Whole Earth Approach"[4,37].

In this global analysis we necessarily had to make broad assumptions about the costs and benefits of conserving or restoring natural habitats, or managing them for agriculture; future analyses, especially at smaller scales, should carefully consider all costs, and should consider the potential management actions implemented in areas that are kept natural, or restored, to adequately estimate their benefits for all features targeted in the analyses (e.g., species, ecosystems and their services, including food provisioning as in here). In our study we quantified benefits as the Area of Habitat for species, but where possible, spatial planning for conservation should consider more direct measures of biodiversity benefits, e.g., the relative suitability for a given species, its expected population size, or its recruitment rate.

When moving from global to national, sub-national, regional and local scales, spatial plans, aided by optimization algorithms will necessarily have to account for opportunity, transaction and management costs[38], which may diminish the perceived efficiency and effectiveness of the spatial plans, but increase their realism and likelihood of success during the implementation phase. Fundamental for the saliency and legitimacy of these plans, and for their uptake will be application of just and equitable participatory processes to decision-making [29].

Ambitious targets

Our analyses lend support for the necessity of adopting the Post-2020 Global Biodiversity Framework Action Target 1 of ensuring that "all land and sea areas globally are under integrated biodiversity-inclusive spatial planning addressing land- and sea-use change, retaining existing intact and wilderness areas". Our analysis cautions against the adoption of biodiversity-only spatial plans, as their implementation could pose substantial risks for food security, up to 10% of pastureland needed for global meat and dairy products demand by 2030. The integration of multiple objectives within inclusive and participatory planning processes, the adoption of outcome-based targets for conservation areas[1,2] and a broader set of area-based conservation measures such as sustainable production areas, recreational areas, and areas under communal or contract-based approaches[3,4], will be fundamental for the success of the proposed Target 3. This would be best achieved through a re-framing of the target towards value retention as opposed to area-protection[2].

With human population and consumption expected to keep increasing beyond 2030, posing additional pressure through habitat loss and degradation and other direct and indirect threats to biodiversity, there is an urgent need to implement ambitious conservation measures such as rezoning of farming activities and conservation-oriented management of natural areas that can conserve important areas for biodiversity while guaranteeing food security[6]. Even ambitious conservation strategies such as the Global Deal for Nature and Half-Earth proposals' goals to protect 30% and ultimately 50% of the planet's surface to conserve most species as well as landscapes and the services they provide[14–16] might be insufficient in the long-term to ensure the persistence of all species at risk of extinction, especially if areas set aside for biodiversity conservation are not placed where they are most needed[11,34].

For the biodiversity crisis to be abated across all ecosystems, specific conservation objectives should be embedded into land-use planning at all levels and all sectors: infrastructure, agriculture, forestry, mining, aquaculture and other extractive and productive activities[39]. In addition, unprecedented global efforts and investments to restore natural habitats[32] as well as transformative changes in consumption and production patterns to mitigate climate change and other pressures to biodiversity[40] will be essential to make sufficient space for nature and allow biodiversity to thrive.

Experimental procedures

Resource availability

Please contact Dr Piero Visconti (visconti@iiasa.ac.at) or Constance Fastré constancefastre@gmail.com for information related to the data and code described in the following experimental procedures section.

Materials availability

No materials were used in this study.

Data and code availability

The dataset generated during this study has been deposited to https://doi.org/10.5281/zenodo.5594628.

The code to replicate figure 2 and instructions to replicate the prioritization is in https://github.com/pierovisconti/integratedSP

Conservation strategies

Using the spatial land-use zoning tool Marxan with Zones, we test the potential effects of implementing three global area-based conservation strategies (ILUP, 30%+ILUP and 30%) based on two action calls proposed in the post-2020 Global Biodiversity Framework, on the conservation of mammal and bird species and on farmland production in 2030. The simulations consist of allocating spatially natural land cover types and farmland (croplands and pastures) across the terrestrial surface (excluding the Antarctic and most of Greenland) to achieve explicit targets set to minimize the extinction risk of species (birds and mammals) and/or farmland production (pasture area, food and biofuel crop production) under different constraints on the spatial allocation for food production (Box 1).

In the Integrated-Land-Use-Planning (ILUP) strategy, we simulate the effect of including at least 50% of land under comprehensive planning to achieve both species conservation and farmland production targets. To do that, we spatially allocate natural land cover types and farmland to achieve pre-defined species conservation targets and farmland production targets. In this strategy, farmland cannot be allocated within the existing PA network except in areas that are presently entirely converted to farmland (Box 1). In the 30% strategy, we investigate the feasibility and effectiveness of setting aside a pre-defined 30% of the world for biodiversity conservation[14]. To do that, we allocate natural land cover types and farmland to achieve farmland production targets only (30% strategy) under the constraint that farmland cannot be allocated in ~30% of land (the 'Biodiversity Areas'). The Biodiversity Areas are considered to be of global significance for biodiversity conservation and represent suitable candidate areas to implement a vision of 30% of land surface managed for biodiversity conservation[16,20,26]. The Biodiversity Areas amount to 34% of the land's surface, covering a little more than 44 million km², and account for all elements of biodiversity represented in both the Dinerstein et al. proposal[14] as well as other recent global studies[16,20,26]. These elements include the global existing PA network[41], the Key Biodiversity Areas (Important Bird Areas and Alliance for Zero extinction sites)[26,42], complemented with 17% of each terrestrial ecoregion needed to address the species-extinction crisis and conserve a global ecological heritage for future generations[20], a network of complementary proposed sites designed to achieve adequate representation of all major terrestrial taxonomic groups comprehensively assessed (birds, mammals, amphibians and crayfishes)[26] and wilderness areas to protect large intact ecosystems[16]. In the 30%+ILUP strategy, we simulate the effects of the two Global Biodiversity post-2020 area-based targets (Target 1: including more than 50% of the land under comprehensive spatial planning and Target 2: protecting 30% of the planet) by allocating natural land cover types and farmland to achieve both species conservation and farmland production targets. In this strategy, farmland cannot be allocated within the Biodiversity Areas. As a result, the ILUP and 30% strategies differ in the spatial restrictions applied to farmland production while the 30%+ILUP adds explicit targets for species conservation (integrated planning for food production and species conservation) to the 30% scenario (Box 1).

In the ILUP and the 30%+ILUP strategies, we define species conservation targets for 4323 and 8541 terrestrial birds and mammals (79% and 85% of the world's known species) for which data on distributional range and habitat affiliation are available from the IUCN Red List database[31]. These area-based targets are designed to be well above the thresholds that the IUCN Red List sets for a species to qualify for the category 'Vulnerable', thereby meeting the goals set by Aichi target 12 and Target 2 of the draft Global Biodiversity Framework post-2020 to minimize extinction risk and improve the conservation status of known threatened species (see section Targets below). In all strategies, we define farmland production targets as pasture area and regional crop production amounts in 2030, projected under a Business-as-Usual (BAU) assumptions based on the 'Middle of the road' SSP2 scenarios[43]. These scenarios are characterized by average land use regulation to mitigate loss of nature, average farmland productivity growth, average impact of food consumption on the environment, combined with regionalized international trade characteristics[44,45] (see section IMAGE 3.0 – Crop production and pasture area projections).

Marxan with Zones analysis

We use the decision-support tool Marxan with Zones (MarZone[46]), that allows for multiple land use zoning, to generate spatial prioritization plans that aim to reach the targets set for species conservation and/or farmland production. We divide the world in grid cells referred to as planning units of 5 arc-minutes (~100 km² at the Equator). Each of these planning units has (1) a value for potential food and biofuel crop yields (total yield across all food and biofuel crops produced in the unit), (2) potential pasture area and (3) two types of penalty costs, related to existing natural vegetation area and farming suitability (see section 'Opportunity and transaction costs of land-cover change' below). We run the algorithm 50 times with 200 million iterations to design near-optimal land cover plans (in terms of cost-efficiency and closeness to achieving all targets). The simulations aim to reconcile biodiversity conservation and food production worldwide (Figure S4 for an illustration of the workflow) by reaching 2030 targets for species conservation and/or for farmland production (food and biofuel crop production and for the pasture area available to grazing).

Formally, we minimize the following objective function:

$$min\left(\sum_p^P \sum_z^Z \sum_i^I c_{i,p,z}\, x_{p,z} + r_s f_s \left(H(t_s - \sum_p^P \sum_z^Z a_{s,p} k_{z,s} x_{p,z})\right)\left(t_s - \sum_p^P \sum_z^Z a_{s,p} k_{z,s} x_{p,z}\right)/t_s\right) \tag{1}$$

Where ci,p,z indicates the cost incurred when assigning planning unit i to zone z (natural land cover types or farmland in the analysis). The costs are described in the section Opportunity and transaction costs of land-use cover change X is a control variable that takes values $\{0,1\}$. Its value is 1 if the planning unit p is in zone z, and 0 otherwise. Each planning unit can only be allocated to one zone per simulation. The zones each planning units can potentially be allocated to are constrained by factors related to biophysical conditions (e.g. farming suitability), logistical aspects (e.g. distance from farmland), tenure (e.g. whether the planning unit is currently within a protected area) and conservation strategy (e.g. Biodiversity Areas in 30% and 30%+ILUP strategies). Zones and zoning constraints are described in detail in the section Land Use – Land Cover allocation. The variable *ts* indicates the feature-specific target to be achieved by solving the zoning problem. This target is expressed as the amount of food and biofuel crops to be produced in each of the world macro-economic regions (tons), the area of pastureland for each macro-economic region (km^2), and area of habitat for each species (km^2). Crop and pasture targets are described in the section IMAGE 3.0 and species targets in the section accordingly named. The variable *as,p* is the amount of feature *s* in planning unit *p* and has the same unit as the respective target. The section Features describes the species, crops and pasture areas for which targets were set, and how their spatial distribution *a* was calculated. The parameter *kz* is a zone-specific parameter that defines whether zone *z* contributes to achieving the target for feature *s* and its calculation is described in the section LULC contribution to target. The parameter *fs* is a feature-specific weighting that allows to give higher or lower priority to achieving specific targets when not all targets can be met. We have set a weight of 1 for all features. The function *H* is the Heaviside function, which takes the value of 0 when its argument is <1 and 0 otherwise. The argument of the Heaviside function here is the feature-specific distance from target, or shortfall. The parameter *rs* is a feature-specific unit cost, which is calculated inside the software prior to optimization as the cost of zoning planning units in order to achieve the target for feature *s*. This parameter is used to transform any relative shortfall in target achievement (the last ratio in the equation) into a feature-specific cost penalty, i.e. the cost it would take to achieve the feature-specific target. This means that the units of the objective function are costs.

The problem is solved by Marxan with zones using the Simulated Annealing algorithm. The problem is conceptually similar to a minimum set problem, where an objective function is minimized subject to constraints. However, Marxan's calculation allows to obtain solutions for unfeasible problems (not all targets can be met), by minimizing the sum of planning unit costs and feature penalty costs. Simulated annealing is a very efficient stochastic global search algorithm that allows to explore the solution space and identify several local minima and, with sufficient annealing iterations and runs, is likely to identify solutions close in performance to the global maximum. The use of a global search algorithm has the advantage of identifying several spatial configurations, all satisfying the logistical constraints we imposed on the placement of different land-use types, thereby capturing some of the uncertainty inherent in creating future scenarios of land-use.

Features - Each planning unit is assigned species, crop and pasture amount values. Species values are calculated as the total area in the planning unit of habitat, AOH[28,47,48] of each mammal and bird species included in the analysis. Using the AOH, *i.e.* clipping unsuitable land-cover and land-uses from range maps, greatly reduces the false presence rate (commission error), without increasing the false absence rate (omission error), and has been shown to substantially increase the efficiency of conservation plans[49]. After excluding all water-dependent species and species lacking data, the analysis considers 4323 mammal and 8541 bird species. Crop values are calculated as the potential total food (7 crop classes) and biofuel (4 crop classes) crop production (in tonnes) estimated from the 2030 scenario projections generated by the Integrated Model to Assess the Global Environment (IMAGE) version 3.0[11]. We estimate the potential 2030 production by interpolating the projected 2030 production (in tons/ha) generated by IMAGE with a 100-kilometer buffer area not classified as bare areas or deserts by IMAGE for that year. We do this to account for uncertainty in the exact location of future farmland development, at the same time as logistical constraints in converting further land for human uses distant from existing infrastructure (transportation network and current farmland). We calculated pasture area as the area available for grazing in km^2, in planning units with high suitability for farming/grazing activities (from the IMAGE model) located within 100 km from the farmland frontier.

Species targets – Unlike most earlier conservation planning analysis, which have used arbitrary representation targets, e.g. an equal percentage target, or a subjective scaling of percentage target as a function of range size[25,26] based on range maps, we design species representation targets with appropriate thresholds for Area of Habitat (AOH). These targets aim at conserving or restoring sufficient habitat for any species to qualify to the lowest category of extinction risk according to IUCN Red List Criteria, (Least Concern). This means that targets may not be smaller than 2200 km² to avoid triggering criterion B2 for the Vulnerable category and no smaller than 80% of the present AOH, to avoid triggering criterion A3c (with a 10% buffer to avoid optimizing zoning exactly to the threshold level for Vulnerable). Targets are capped at 1 million km² for the species with extremely large ranges[26]. Fastré et al. [27] have conducted sensitivity of conservation priorities analyses using these targets, showing that they provide equitable conservation across regions and species, where equitable means affording the same likelihood of persistence, as approximated through IUCN extinction risk criteria. We do not consider IUCN Red List sub-criteria, e.g. that trends have to occur over 3 generations, because this is not a Red List assessment, but a conservation planning exercise aimed at providing guidance on spatial zoning to meet biodiversity targets and food production. Our premise is that while we optimize land-use to ensure that the AOH of each species meets at least the target levels, on-the-ground management of these areas, (including species reintroduction, and mitigation of other threats to biodiversity, where necessary), will ensure that these areas support thriving populations. In other words, AOH of species *s* effectively managed for the persistence of $s \approx \mathrm{AOO}_s$; we therefore refer to AOO (Area of Occupancy) for the reminder of the manuscript unless we refer specifically to area of habitat.

IMAGE 3.0 – Crop production and pasture area projections

For all conservation strategies, we use the projected total regional food and biofuel crop production and pasture area in 2030 modelled by IMAGE as regional targets for farmland production in the SSP2 *Middle of the Road Scenario*, which defines a Business as Usual scenario of socio-economic development, hence here referred to as BAU. IMAGE 3.0[11,19] is an integrated assessment modelling framework that simulates the interactions between human activities and the environment[11], to explore long-term global environmental change and policy options in the areas of climate, land and sustainable development. The framework comprises of several sub-models describing land use, farmland economy, the energy system, natural vegetation, hydrology, and the climate system. IMAGE models economic changes at the level of 26 macro-regions (Figure S5), while the environmental components work at the grid level to account for heterogeneities in environmental circumstances. A detailed description of all parameters exchanged between the various IMAGE sub-models is available at http://models.pbl.nl/image/index.php/IMAGE_framework. We apply assumptions and parameters from the SSP2 Business as Usual scenario in 2030 for all three strategies implemented in the MarZone analysis, encompassing crop production, potential productivity and farming suitability on a grid basis, and targets for crop production and pasture areas at the regional level.

While there is considerable variability in land-use projections amongst land-use models and scenarios[50], variability accrues over time and is most prominent in the second half of the 21st century. Differences in land use projections result from a combination of different model architectures and philosophies, inherent uncertainties on modelled processes such as for example irrigation of cropland, and differences about how to parameterize these processes along various storylines such as the SSPs. Some of these reflect true uncertainties around the mechanisms and parameters, so no model in particular is necessarily more correct than others, which is why we choose to use IMAGE, the most mature Integrated Assessment model and the most widely used for global environmental studies. IMAGE was found by Popp et al.[50] to be a "median" model, in the sense that projected total amount of different land-uses that were in the middle of the model ensemble tested. Our choice of model, and our projection to the year 2030, the most meaningful time-frame in light of the SDGs and post-2020 Biodiversity agenda, are aimed at capturing the main land-use trends, while avoiding a proliferation of simulations and full treatment of uncertainties, which is beyond the scope of this study.

Land Use – Land Cover (LULC) allocation

We use MarZone to assign planning units to one of twenty-six Land Use – Land Cover classes (Table S1). We use the same 22 land cover classes described by Global Land Cover 2000 (GLC2000, http://forobs.jrc.ec.europa.eu/products/glc2000/legend.php), to which we added a pasture land use (LULC 24), two land classes representing shared grazing land use, either in forest or natural vegetation types (Mosaic Tree Pastures and Mosaic Natural Pastures, LULC 25 and 26) and a mixed land use (50% crops and 50% pasture, LULC 23).

To keep LULC allocation realistic, we first constrain planning units with at least half their area currently built-up or covered by deserts or bare areas to remain in the built-up, desert or bare areas LULC, respectively. Due to lack of credible models of built-up areas expansion, we assume built-up areas to remain static to 2030. Second, we restrict LULC allocation within the 2018 Protected Area network (PA network, ILUP strategy) or within the Biodiversity Areas (30%+ILUP and 30% strategies). For the 2018 PA network, we use a map obtained from https://www.protectedplanet.net/ from which we removed UNESCO Biosphere Reserves, proposed sites, sites with unknown designation status and sites lacking both spatial boundaries and reported extent, as described in Butchart *et al.*[26]. In the ILUP scenario, we restrict the LULC allocation of the PA network planning units to the most common LULC currently present in that planning unit, ensuring the 2018 PA network remains in its current state and preventing further conversion to farming activities. In both 30% strategies, Biodiversity Areas planning units are restricted to their major current natural class or to any of the shared land use classes (LULC 17, 18, 26 and 27) if a planning unit is already converted to farming activities. For each strategy and for all remaining planning units (*i.e.* outside of built-up, bare, PA network or Biodiversity Areas), LULC allocation is restricted to any of the LULC types currently present in that planning unit (extracted from the GLC2000). To ensure farmland is only allocated where logistically feasible, e.g. not in remote and intact areas, we take the conservative assumption of restricting the relocation of cropland, grazing or shared land uses (land uses 16, 17, 18, 24, 25 and 26) in areas within a maximum distance of 100 km from the planning units projected to be exploited for croplands or pasture in 2030 by IMAGE. Finally, to prevent the allocation of natural cover types in unsuitable and/or incongruous areas and to ensure that species will be able to spread to restored habitats, we only allow restoration to be carried out in planning units that currently contain some natural habitat (or within 10 km of where intact habitats remain).

Land Use – Land Cover contribution to target

The LULC contribution in MarZone determines the amount of each feature that contributes to reach user-defined targets when a planning unit is allocated to a specific LULC class. For all mammal and bird species included in the analysis, we assign a LULC contribution value of 100% to any LULC defined as suitable for the species by the IUCN Red List of threatened species (http://www.iucnredlist.org/). We retrieved the IUCN Habitat preferences for all terrestrial birds and mammals from the IUCN Red List Database in February 2018. To apply the IUCN habitat preferences to GLC2000 land cover classes, we use a crosswalk table modified from Foden et al., 2013[51] based on guidance of IUCN habitat classes[43]. Cropland (16) and pastureland (24), fully contribute to achieving targets for crop production and pastureland, respectively. We assume that the land allocated to mixed uses will be, in average, equally divided into natural land cover classes and farmland, therefore assigning a planning unit to Mosaic Crop LULC classes (17 and 18) would only contribute half of the potential crop yield to crop targets achievement, Mosaic Pastureland classes (26 and 27), contribute only half their area to pastureland targets. In both cases, we assume that in average the natural and anthropogenic component of these mixed uses would be managed in ways that deliver half of the benefits for species or food production than if the area was managed to maximize one of the objective only. We recognize that the food production and biodiversity benefits of mosaic landscapes are likely to vary spatially and depending on the management intensity and spatial configuration, something we cannot realistically account for spatially here. Similarly, we assign a 50% contribution value to the MixedCropsPastures LULC (25) for both crops and pastures features, under the assumption that, in average these mixed land-uses are equally composed of pastures and cropland, but recognizing that their relative proportion would vary depending on the type of management systems and resulting farmland landscapes. We did not perform sensitivity testing on LULC contribution values. Because we assume that habitats will be completely restored by 2030, it must be noted that the strategies simulated here may overestimate the realized amount of area of habitat contributing to species conservation.

Opportunity and transaction costs of land-use change

To find a solution that minimizes the opportunity cost for farming worldwide while avoiding the widespread conversion of natural areas, we apply two types of penalties to re-zoning planning units relative to present conditions: a farming suitability and a natural penalty (Figure S6). Specifically, to penalize habitat restoration in areas that are highly suitable for farming activities, we use the agricultural suitability values of each planning unit in 2030 by IMAGE as the *farming suitability penalty*. IMAGE determines suitability following an empirical allocation algorithm with four drivers[19]: potential crop yield as modelled by LPJmL, accessibility from Nelson et al. 2008[52], population density from the HYDE database[53], and terrain slope index from the Harmonized World Soil Database[54]. The suitability penalty is fully incurred when planning units are allocated to any LULC, except for farming uses (16, 24 and 25) which incur no penalty, and shared land uses (17, 18, 26, 27), which incur half of the penalty. The transaction cost of converting natural areas to farmland, *the natural penalty*, is calculated as the proportion of current natural LULC (according to GLC2000) in each planning unit. This cost is incurred when planning units are allocated to farming uses (16, 24 and 25, full penalty) and shared uses (17, 18, 26, 27, half penalty).

Simulations evaluation

We use each of the 50 solutions generated by MarZone to evaluate the potential impacts of implementing each strategy on species conservation and farmland production. The impact on species conservation is calculated as the number of mammal and bird species remaining at risk of extinction (i.e., species that fail to meet their targets). The impact on food security is calculated as the amount of food crop production and pasture area missing to reach the targets (food production shortfalls, Figure and Extended Figure S3). Additionally, we calculate the percentage of land remaining in a natural and a degraded state (areas that are currently in a natural state or farmed according to the current LULC map (GLC2000) and remain so in the solutions, respectively), requiring restoration activities (areas that are farmed in GLC2000 that are allocated to natural LULC types in the solutions) or being degraded (areas that are currently in a natural state in GLC2000 and are converted to farming uses in the solutions). We calculate these area statistics for each continent and globally (Figure S2). The percentage of the terrestrial global land requiring conservation is calculated as the combination of the percentage of land that remains in a natural state or must be restored by 2030 in our solutions (natural areas, in blue in Figure S2). Finally, we calculate the percentage of natural land cover remaining in the solutions for each ecoregion of the world (Figure S4).

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Author Contributions

PV conceived the idea, PV and CF designed the study. WJVZ provided the IMAGE land claim data, JW provided the Biodiversity Area spatial data. CF performed the analyses. CF and PV interpreted the results and wrote the manuscript with input from WJVZ and JW.

Declaration of Interests

The authors declare no competing interests

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Boxes

Box 1. Strategies simulated in the analysis aimed at assessing two proposals for global area-based conservation targets proposed in the post-2020 Global Biodiversity Framework

ILUP strategy: This strategy is designed to simulate how including most of the terrestrial land surface under comprehensive land use planning (Target 1 of the Global Biodiversity Framework) can achieve both species conservation and global farmland production by 2030. To simulate this strategy, we spatially allocate natural land cover types and farmlands outside of the present Protected Areas (PA) network to meet both species conservation and farmland production targets. Within the PA network, the present fractional land-cover (according to IMAGE for the year 2015) remains unaltered until 2030.

30% strategy: This strategy is designed to simulate how limiting species conservation actions to a pre-defined 30% of the world would impact both species conservation and global farmland production (Target 2 of the Global Biodiversity Framework).

To simulate this strategy, we spatially allocate natural land cover types and farmlands to meet farmland production targets, under the constraint that farmland cannot be allocated within the Biodiversity Areas. In this strategy, the Biodiversity Areas are fully conserved or restored into their current most abundant natural land cover type or to any of the shared land uses if they are entirely converted to farmlands already.

30%+ILUP strategy: This strategy is designed to simulate the impacts of setting aside a pre-defined 30% of the world to ensure species conservation (Target 1 of the Global Biodiversity Framework), while including the remaining of the terrestrial land surface under comprehensive land use planning (Target 2 of the Global Biodiversity Framework) to achieve both species conservation and global farmland production.

To simulate this strategy, we spatially allocate natural land cover types and farmlands to meet species conservation and farmland production targets, under the constraint that farmlands cannot be allocated within the Biodiversity Areas. The Biodiversity Areas are fully conserved, or restored into their current most abundant natural land cover type or to any of the shared land uses if they are entirely converted to farming activities already.

Figures

Figure 1 Distribution on the number of mammal and bird species at risk of extinction per ecoregion with bars representing (from left to right) the percentage of food crop production, pasture area shortfalls and mammal and bird at risk of extinction following the BAU pathway for the A) ILUP, B) 30% and C) 30%+ILUP strategies

Figure 2 Trade-off between percentage pasture area shortfall and mammal species at risk of extinction (A) and between the percentage of crop production shortfalls and the percentage of birds species at risk of extinction (B) for the 30%, 30%+ILUP and ILUP strategies. Dots indicate the mean shortfalls across 50 runs. Lines within the circles indicate maximum and minimum shortfall values obtained among runs.