Coordinated intensification to reconcile the 'zero hunger' and 'life on land' Sustainable Development Goals

Abstract

The Sustainable Development Goals (SDGs) encourage nations to substantially increase food production to achieve zero hunger (SDG 2) while preserving life on land (SDG 15). A key question is how to reconcile these potentially competing goals spatially. We use integer linear programming to develop an 'integrated land use planning framework' that identifies the optimal allocation of 17 crops under different hypothetical conservation targets while meeting agricultural demands by 2030. Intensifying existing cropland to maximum yield before allocating new cropland would reduce land requirement by 43% versus cropland expansion without intensification. Even with yield gap closure, tropical and sub-tropical crops still require expansion, primarily allocated to Venezuela, eastern Brazil, Congo Basin, Myanmar and Indonesia. Enforcement of protected areas, via avoiding conversion in 75% of Key Biodiversity Areas and 65% of intact areas, is vital to attain biodiversity targets but bears large opportunity costs, with agricultural rents dropping from $4.1 to $2.8 trillion. Although nationally constrained forest conservation efforts would earn 9% less agricultural rents compared to globally coordinated conservation solutions, they reduced intact habitat and forest loss (43 and 35% reduction). Our results demonstrate that careful choice of the allocation of future cropland expansion, could dramatically reduce—but not eliminate—the tradeoffs between the SDGs for food production and land biodiversity conservation.

Keywords: land-use systems; agricultural intensification; telecoupling; spatial optimization.

Earth is undergoing a global biodiversity crisis, with one of the main causes being rampant habitat loss. Over 2.3 million km^2 of forest has been lost since 2000 (Hansen et al., 2013), and as a result, about one million species are currently threatened with extinction (Diaz et al., 2019). The biodiversity crisis occurs in parallel with 795 million people suffering from food insecurity (Von Grebmer et al., 2016). In response to these challenges, world leaders committed to the Sustainable Development Goals (SDGs) in 2015, which aim to eradicate hunger (SDG 2 zero hunger) and poverty from the planet by 2030 (United Nations, 2017). At the same time, the SDGs also aim to preserve and enhance natural life on land and water (SDGs 14 and 15) (Griggs et al., 2013).

Eradicating global hunger and poverty, while meeting ever-increasing food demands, requires substantially increasing food production (Godfray et al., 2010), as well as broad-scale societal changes, including reduced food waste, reduced over-consumption, and reduced meat consumption. Increasing food production is—through more demand for agricultural land—necessarily at odds with enhancing and protecting biodiversity (Gao and Bryan, 2017; Phalan et al., 2011).

Strong inherent trade-offs between SDGs 2 and 15 make coordinated implementation challenging. Integrated cross-sectoral analyses have identified trade-offs and operating spaces to attain sustainable outcomes nationally (e.g. Collste et al., 2017; Gao and Bryan, 2017 in Tanzania and Australia respectively) and globally (Obersteiner et al., 2016; Pastor et al., 2019). For instance, Obersteiner et al. (2016) revealed that policies targeting sustainable consumption and production (SGD12) are the most effective ones to alleviate trade-offs between environmental conservation and food production. Although the interconnectedness between the SDGs and the trade-offs that competing SDGs would impose on nature are increasingly recognized (McGowan et al., 2019; Nerini et al., 2018), a key question is how social and environmental SDGs can be simultaneously achieved spatially.

Conservation planning may reconcile competing objectives through spatial optimization that either minimizes conservation costs while achieving biodiversity targets, or maximizing biodiversity gains given a limited conservation budget (Delavenne et al., 2012; Hermoso et al., 2010; Levin et al., 2013; Nhancale and Smith, 2011). Here we expand conservation planning into ‘integrated land use planning’ by integrating biodiversity (SDG 15 life on land) and food provision targets (SDG 2 Zero Hunger) within the same spatial optimization framework. As closing yield gaps is likely insufficient to meet future food demands (Tilman et al., 2011), it is necessary to study where to put new cropland while preserving biodiversity once yield gaps are closed.

We use this integrated land use planning framework to: (i) identify which crops, after yield gap closure, still require cropland expansion; (ii) identify where future crop expansion should occur to reconcile conservation and food production; (iii) explore the trade-offs between agricultural rents of food production and conservation targets; and (iv) compare the outcomes between nationally constrained and globally coordinated strategies for limited deforestation.

Our optimization used integer linear programming combined with geographic information systems to maximize agricultural rents globally from 17 crops that are the greatest in terms of area and value (banana, beans, cassava, cocoa, coconut, coffee, cotton, cowpea, groundnut, maize, millet, oil palm, rice, sorghum, soybean, sugarcane, and wheat). We assumed that yield gaps would first be closed in existing cropland for the 17 crops prior to further habitat conversion to agriculture (see *Methods*). The maximization was subject to meeting global demands for each crop by the 2030 target for the SDGs under four hypothetical scenarios: (Table 1, see Methods): i) cropland expansion is possible in any available land after existing yield gaps are closed (*baseline scenario I*); ii) similar to the baseline scenario I but cropland is not intensified to close yield gaps before cropland expansion (*baseline scenario II*); iii) forests cannot be reduced by more than 5% at the global (*forest conservation scenario I*) or vi) at the national (*forest conservation scenario II*) levels. We evaluate each optimal spatial solution of where to allocate new cropland under each scenario in terms of area converted (in different habitat types and conservation protection status), agricultural rents generated, and projected number of birds and mammals to become extinct globally due to conversion using species-area relationship models. Results here are not predictions of what will happen in the future, but are projected social and environmental outcomes under different hypothetical scenarios.

Results

Which crops need expansion and where should they go?

Closing yield gaps across existing crop distributions under baseline scenario I would be able to meet 2030 demand of most crops except for the tropical and sub-tropical crops of banana, cassava, coconut, cotton, oil palm and sugarcane, thus requiring further cropland expansion. The deficit in demand would be highest for sugarcane, cassava and oil palm (433, 80, and 48 million tons, respectively, Table S1). Cotton and sugarcane were the crops that required the most land to meet their future demands (collectively around 53% of total new cropland area, Fig. 1).

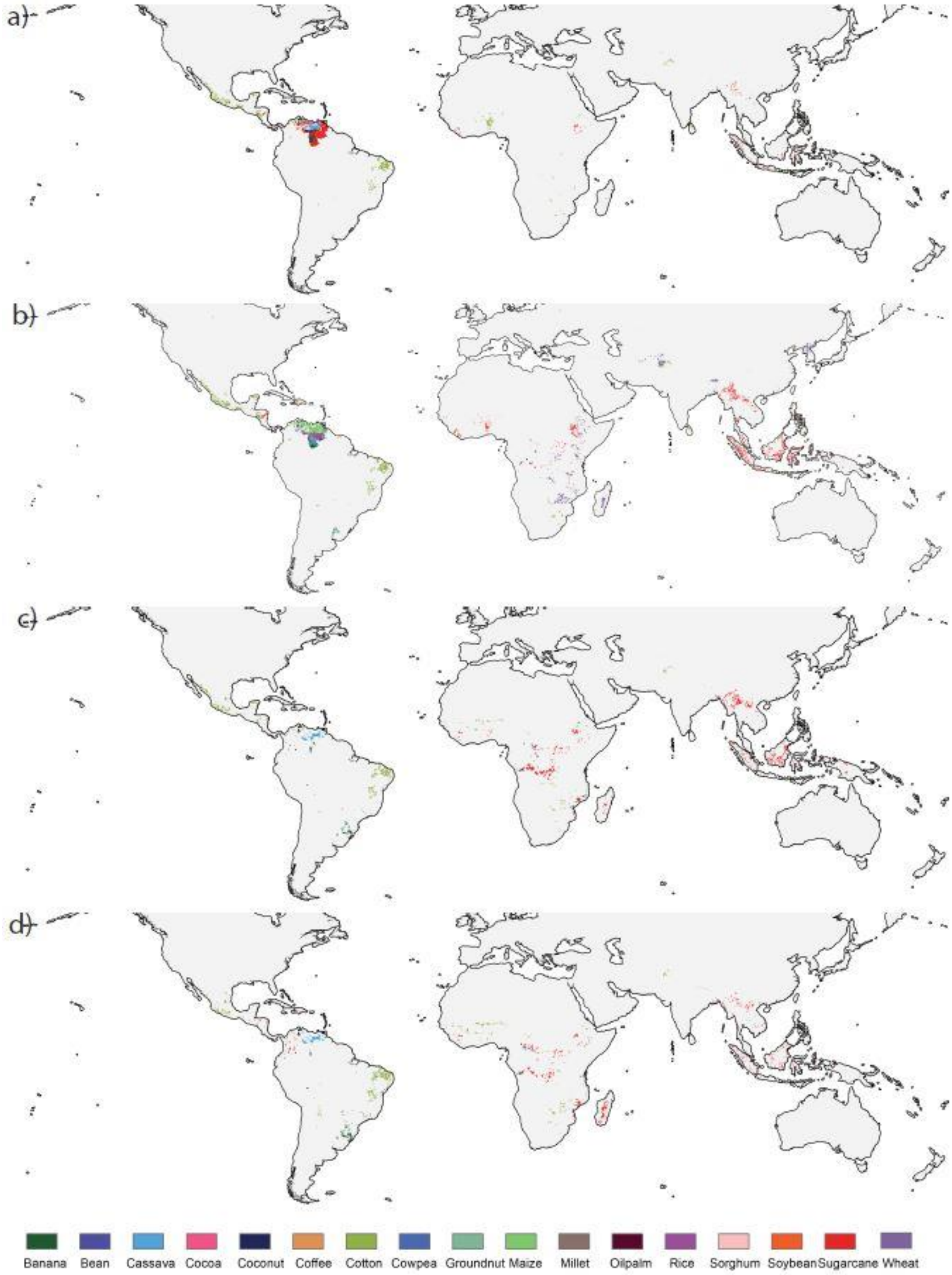

Fig. 1. New cropland allocation maps according to the optimization model showing where cropland cultivating each crop should be allocated to maximize rent subject to environmental and human food demand constraints in the a) baseline scenario I; b) baseline scenario II; c) forest conservation scenario I; and d) forest conservation scenario II. Only regions with new cropland allocation are shown on the map.

To meet the deficit in demand, across the four different scenarios, the spatial patterns of new cropland allocation collectively exhibited some similarities. Locations selected for cropland expansion were mainly along the tropical belt including the Guiana Shield (mainly Venezuela), the Brazilian Shield, the Western African coast, Eastern African plateaus and valleys, and South-east Asia (SEA) (Fig. 1). Across continents, South America had most cropland allocation while Europe and Oceania had the least (Fig. 2). Conversely, in the baseline scenario II with no intensification before cropland allocation, there were much larger-scale land allocation in Africa and SEA. In the forest conservation scenario I that required global coordination, new cropland shifted away from Venezuela to SEA (Myanmar, Laos, and Indonesia) and Africa (Democratic Republic of Congo, Ethiopia, Zimbabwe, Mozambique, and Madagascar, Fig. 1). These are areas with high potential agricultural rents (high potential yields and low production costs; Fig. S1) for the crops requiring further production. In addition, when forest conservation was set as national targets in forest conservation scenario II, new cropland allocation was scattered across more countries instead of being concentrated in a just a few countries.

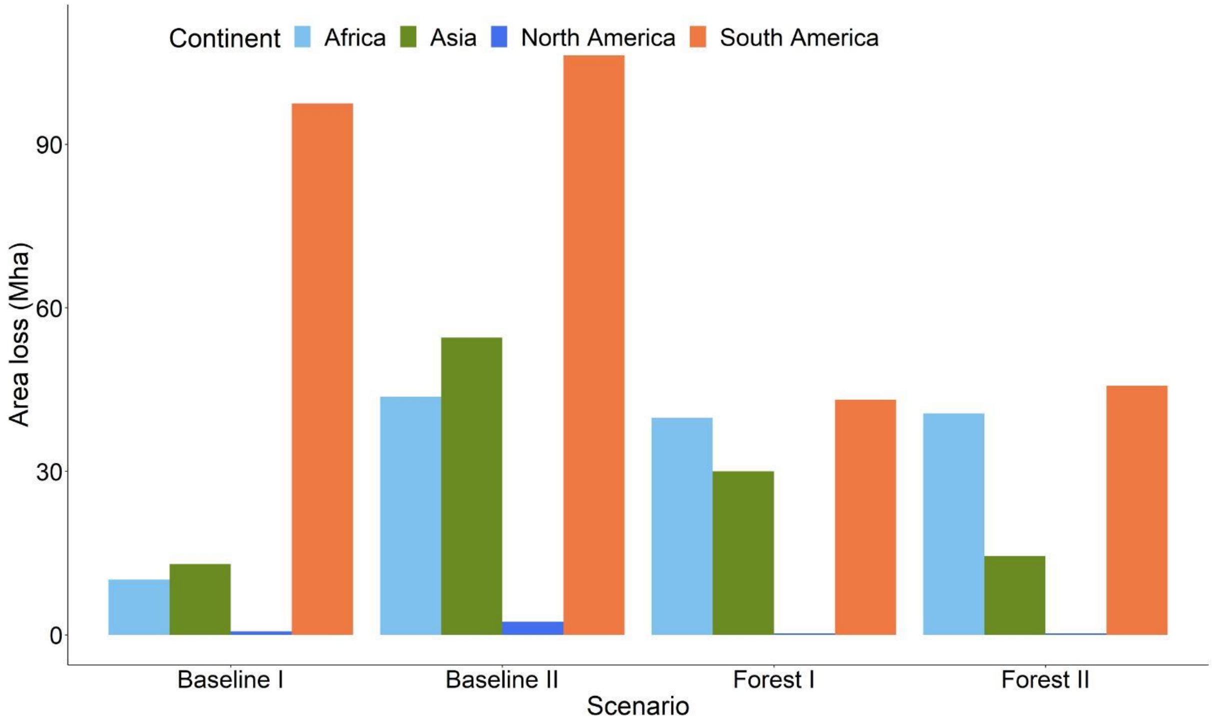

Fig. 2. Area lost due to new cropland allocation in each continent in each scenario. Forest I=Forest conservation scenario I (global coordination); and Forest II=Forest conservation scenario II (national constrained). No allocation in the Antarctic and the Oceania. Allocation in Europe was not shown in the graph since it has new cropland only in the baseline scenario II (0.04 million hectare).

Trade-offs between different conservation targets

Comparison between the baseline scenario I and baseline scenario II revealed the effectiveness of intensification in terms of reducing habitat loss (from 211 Mha to 121 Mha) and species loss (from 54.93 to 23.67 bird species and from 4.77 to 1.97 mammal species extinctions) (Table 2 & Fig. 3). Although less PAs and intact habitats were converted after yield gap closure in baseline scenario I due to less new cropland required, their increased proportional contribution to total converted area (from 57% to 67%, and from 23% to 32%, respectively) indicated that these areas are prioritized during the new cropland allocation process. This suggested that PAs and intact habitats might have high potential to generate large agricultural rents the tropics (see SI for additional conservation scenarios that also reflected this pattern).

Scenario	Baseline I	Baseline II	Forest conservation I	Forest conservation II
Total area ($\times 10^8$ ha)	1.21	2.11	1.13	1.01
Rent ($\times 10^{12}$)	4.09	12.75	2.57	2.34
Area of intact habitat ($\times 10^7$ ha)	3.91	4.75	1.01	0.58
Area of forest ($\times 10^7$ ha)	8.19	14.31	7.75	5.08
Area of grassland ($\times 10^7$ ha)	1.58	2.75	1.32	2.16
Area of shrubland ($\times 10^7$ ha)	1.76	2.96	1.85	2.34
Area of wetland ($\times 10^6$ ha)	1.92	2.66	1.83	2.38
Area of PAs ($\times 10^7$ ha)	8.1	12.03	0	0
Area of KBAs ($\times 10^7$ ha)	2.74	4.26	0	0
Number of bird species extinct	23.67	54.93	10.12	13.45
Number of mammal species extinct	1.97	4.77	1.98	1.58

Table 2. Characteristics of portfolios selected with different conservation strategies to maximize agricultural rent, considering human food demand and environmental constraints. Rent is in 2016 USD.

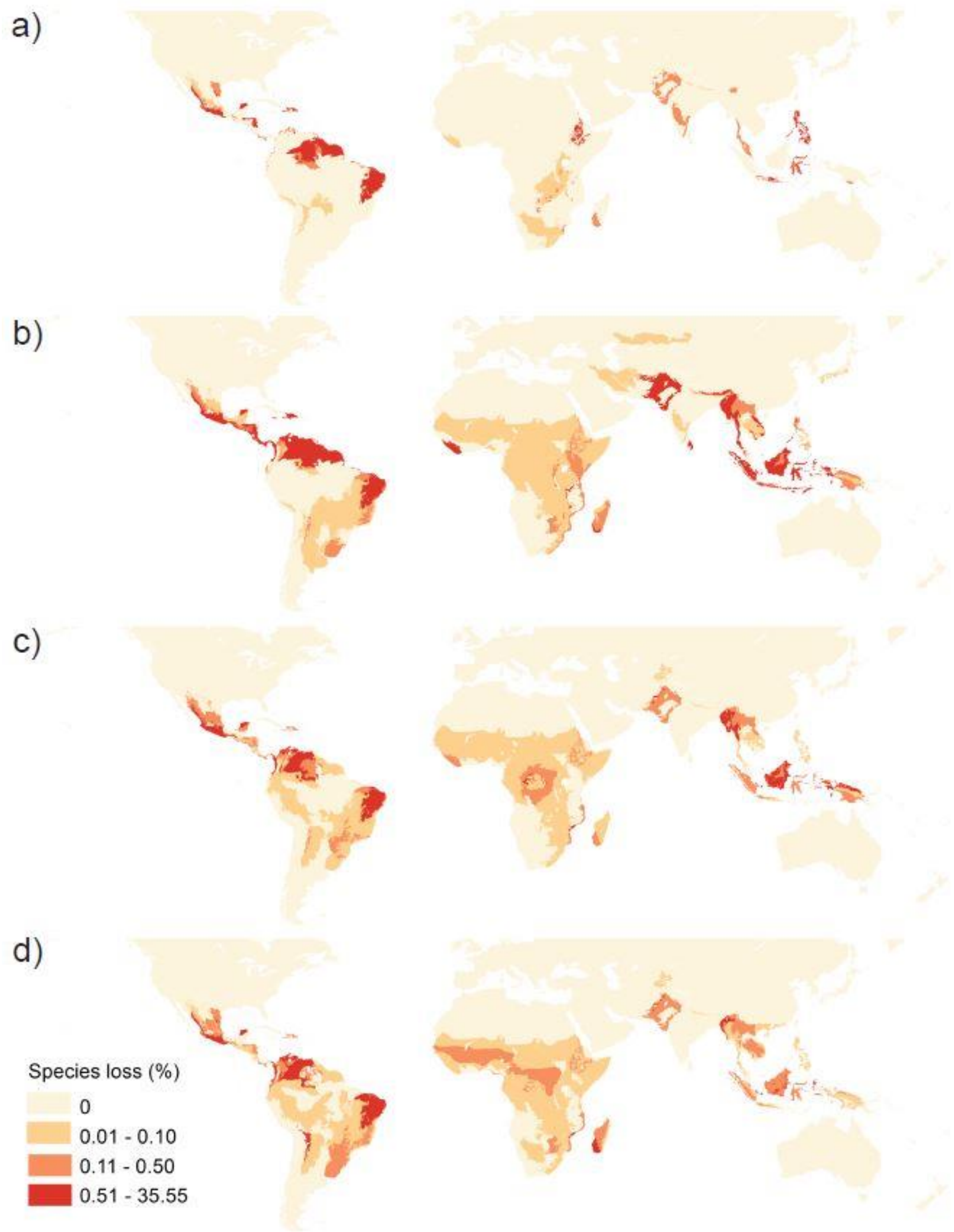

Fig. 3. Percentage of species loss (bird and mammal combined) in each ecoregion due to new cropland allocation in the a) baseline scenario I; b) baseline scenario II; c) forest conservation scenario I; and d) forest conservation scenario II. Only regions with new cropland allocation are shown on the map.

When forest conservation is globally coordinated (forest conservation scenario I), via forest avoidance and PA exclusion, conversion shifted mainly to shrubland habitats. While total area converted was reduced slightly compared to the baseline scenario I (from 121Mha to 113 Mha), the drop in agricultural rent was more dramatic (from $4.09 to $2.57 trillion), suggesting the higher rent generation potential of forests compared to shrubland in general. Forest conservation and PA exclusion also showed high capacity to protect intact habitat and reduce species loss (Table 2). The additional PA exclusion scenarios presented in SI illustrated that exclusion of PAs alone from conversion also reduced Key Biodiversity Area (KBAs) conversion (Tables S2 & Table S3) from 27 to 7 million hectares of converted KBAs with respect to baseline scenario I under with yield gap closure.

Globally coordinated versus nationally constrained conservation

In the forest conservation scenario I (where globally forest loss should be less than 5%), there were 19 countries with more than 5% loss of forests within their territories. They were mainly African countries and Republic of Congo had the largest gap between the actual and 5% threshold loss (Fig. 4). Compared to the forest conservation scenario II (no nation could lose more than 5% of its forests), global forest conservation had higher agricultural rents generated (from $2.34 to $2.57 trillion) and better bird species conservation performance, with bird species extinction numbers lowered from 13.45 to 10.12 (Table 2 & Fig. 3).

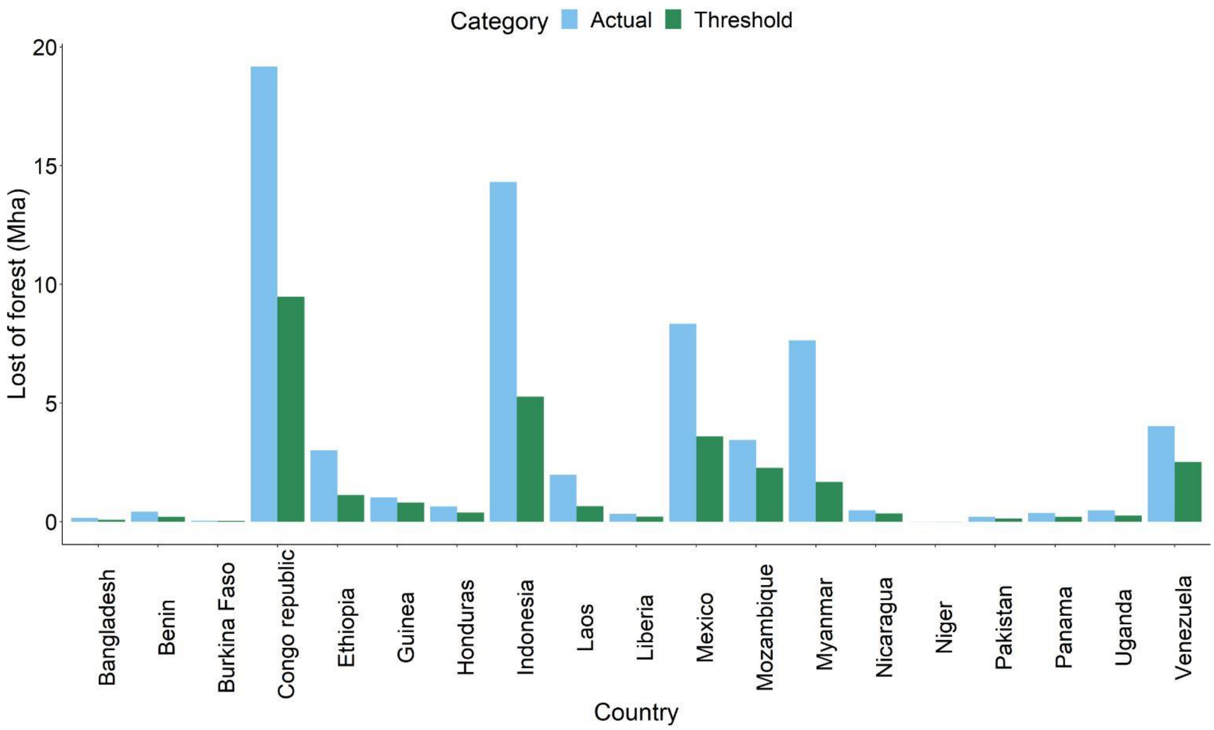

Fig. 4. Countries with more than 5% forest loss in the forest conservation scenario I when the less than 5% forest loss is set as a global target without national constraints. The 'threshold' column shows the maximum amount of forest could be lost in each country according to a less than 5% forest loss criteria, the 'actual' column shows actual forest loss in each country due to allocation of new cropland.

The most noticeable changes were, however, in the reduced area of intact habitat (5.8 Mha) and forests (50.8 Mha) converted in the forest conservation scenario II (nationally constrained) compared to the forest conservation scenario I (globally coordinated) (10.1 and 77.5 Mha, respectively). These reductions were at the expense of large losses in other habitats (grassland, shrubland and wetlands, Table2) in the forest conservation scenario II. Similar patterns were found in the comparison of the forest conservation scenarios under the condition of no yield gap closure (Supplementary Information).

Discussion

Our results show that new cropland would need to be located mainly along the tropical belt, where most of the unused, suitable land for agriculture resides (Gibbs et al., 2010). Needing to place future cropland in hyper diverse tropical regions implies a direct confrontation between food production (SDG 2) and life on land (SDG 15). But despite the tradeoff between SDGs 2 and 15 in the tropics, our results suggest that careful planning of the locations where new cropland is allocated can substantially reduce impacts on biodiversity.

The first fundamental step to reduce the tradeoff is enhanced protected area management in the tropics. Our results demonstrate that, relative to the baseline, agricultural demands could be met with about one third of intact habitat area loss, one quarter of KBAs area loss and two thirds of projected bird extinctions if protected areas are excluded from conversion (comparing baseline scenario I against PA exclusion scenario). The key role of protected areas in protecting tropical biodiversity and constraining agricultural expansion contrasts with previous research suggesting that PAs are biased towards higher altitude, steeper slopes, and further distances to roads (Joppa and Pfaff, 2009). This shows that the tropical fraction of the PA network does focus on halting declines of biodiversity under imminent threats and that tropical PAs are facing a tremendous pressure for agricultural conversion. This would explain pervasive encroachment within protected areas (Spracklen et al., 2015) and of protected area downgrading, downsizing, and degazettement (PADDD) due to agricultural conversion (Kroner et al., 2019; Symes et al., 2016). Therefore, tropical protected area management—protection from direct conversion and protection from degazettement and then conversion—should be a top priority if tradeoffs between SDGs 2 and 15 are to be mitigated. For example, a global convention on no PADDD or effective PAs enforcement for at least 30 years would be fundamental for reconciliation of SDGs 2 and 15.

Despite improved outcomes for biodiversity and habitat protection associated with enhanced protected area management scenario (PA exclusion scenario in SI), the scenario carries a substantial economic cost. Agricultural rents could be reduced by half owing to higher production costs because less accessible areas are converted. This suggests food would be costlier, which could undermine zero hunger (SDG 2), increase inequality (SDG 10, costlier food would be harder to afford by lower income communities), and restrict economic growth (SDG 8). Studying these ramifications would require further research with multi-sectoral economic models (Obersteiner et al., 2016; Pastor et al., 2019). For example, a recent study has suggested optimization frameworks to consider the trade-offs among conservation (SDG 15), equity (SDG 10), and climate change (SDG 13) (Palomo et al., 2019).

The results show that, while the nationally constrained solutions (forest conservation scenario II) greatly reduced forest (35% less) and intact habitat (43% less) conversion, they have relatively less deviation from the globally coordinated efforts (forest conservation scenario I) in terms of agricultural rent losses (12% lower) and biodiversity losses (32% greater bird species extinction but 20% less mammal species extinction). This is in contrast to a previous study on land use planning for sustainable intensification, which found that globally coordinated plans could reduce much more projected biodiversity loss (Egli et al., 2018). The globally coordinated biodiversity conservation plans depicted could be unrealistic because they require agreement across multiple nations. National-constrained solutions compared with globally coordinated optimal solutions allows evaluating the feasibility of the interventions while respecting national sovereignties in terms of biodiversity conservation (Runting et al., 2015). Our results also show that reconciling SDGs 2 and 15 could largely depend on a few tropical nations for additional food production (e.g. Venezuela, Brazil, DRC, Mozambique, Myanmar, Laos, Indonesia). While this would undoubtedly make coordination easier than a global response, coordination among these countries still face challenges (Mason et al., 2020). In addition, complimentary strategies are required to make sure that habitats spared from cropland expansion in other countries are to be conserved instead of being lost to other activities (Phalan et al., 2016). Payment for Ecosystem Services schemes, including Reducing Emissions from Deforestation and Forest Degradation (REDD+), could play a key role (Phelps et al., 2013).

Future cropland expansion that minimizes tradeoffs between SDG 2 and 15 could concentrate in a few tropical nations, suggesting these nations would receive the majority of the agricultural rents at the expense of their natural capital. This allocation may neither be an equitable solution in terms of employment or income generation. It may also be at odds with the national food security policies of other nations, leading to more scattered food production and less-than-optimal biodiversity outcomes (Agarwal, 2014). For example, Senegal is investing heavily in the rice sector to gain self-sufficiency (Diagne et al., 2013) although it is not the best location to produce rice according to our integrated land use planning results. In addition, factors such as lack of political stability might influence the ability of a region to close yield gaps by creating barriers to investment, infrastructure, new technology or new crop varieties (Erb et al., 2012; Kimenyi et al., 2014).

Our models presented the potential trade-offs and synergies between SDG2 and SDG15 and compared different hypothetical conservation strategies. However, there are several fundamental limitations. Firstly, besides the scenarios presented here, conservation agriculture (Kassam et al., 2019) and shared landscapes (Ellis and Mehrabi, 2019) are other potential strategies to reconcile these two goals and worth further research. In addition, although our model has the ability to generate polyculture results if planning units are tiny enough, this requires extremely high computational power and high-resolution data sources. Therefore, current cropland allocation patterns have to remain to be monoculture if considering individual planning unit. Moreover, model outputs are likely to vary if parameter estimates used in the models were different or assumptions were violated. For example, crop yield closure could be a long time effort, climate change might affect potential yield, and other measures such as mixed cropping could also increase crop production. Crop demand is likely to vary if future demand does not follow past trends. Fuel cost and driver cost would also change when crops are transported to international markets instead of nearest large cities. Economies of scale might affect crop price and productions costs. We therefore conducted a sensitivity analysis through increasing and decreasing individual parameter values by 10% under the baseline scenario I condition (see Supplementary Information Figure S6 for the results). The sensitivity analysis, in comparison with baseline scenario I results, showed that model outputs are most sensitive to the uncertainty of future crop demand, crop price, and crop yield. Variation could be as high as around 40% of original values if demand diverged by 10%. This means that when the assumption that demand would follow its historical trend is violated, it could change the results the most, possibly because varying demand means converting much more/less lower-fertility land. This is a plausible scenario considering new demand of crops are emerging, but demand is less likely to diverge too much within only 10 years. Uncertainty of estimates on the other parameter values has very limited influences, mostly below 3%. In particular, the influence of capital, fuel and driver cost value uncertainties on model outputs are almost negligible. This sensitivity analysis indicate that it is most critical to better estimate values of crop demand, price, and future yield to improve projection accuracy. Future research on data collection should give these parameters high priority.

Conclusion

We developed an integrated land use planning modelling framework to reconcile agricultural production and biodiversity conservation (SDGs 2 and 15) under different hypothetical scenarios. Yield gap closure could save a large amount of land, and thus greatly reduce species extinction. The five crops that would require further expansion by 2030, even if yields gaps are closed, are tropical crops. Protected areas are key to attaining the biodiversity targets by resisting conversion pressure associated with large agricultural opportunity costs to ensure that intact areas and KBAs remain. We show that although globally coordinated conservation solutions attain higher agricultural rents and less bird species extinction, politically more feasible nationally constrained solutions are able to greatly reduced intact habitat and forest loss without a large reduction of agricultural rents. Our results thus demonstrate that the careful design of the future cropland allocation could dramatically reduce the tradeoffs between the SDGs for food production and land biodiversity conservation.

Conflict of interest

The authors declare no conflicts of interests.

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Methods

Overview

We created a human-centred integrated land use planning model to plan for the distribution of new cropland. In this model, we aimed to maximize the amount of agricultural rents received by farmers, within constraints of both human crop demand satisfaction and conservation targets achievement. Maximising agricultural rents ensures cropland occur in areas where it generates the most profit (such as via lower production and transport costs). We used integer linear programming to find the optimal solution and applied the model to four different hypothetical scenarios with various conservation criteria to investigate their influences on new cropland allocation. We conducted data extraction and all spatial analysis in ArcMap (version 10.3) and used the Gurobi package (version 8.1) (Gurobi optimization LLC, 2019) in R (version 3.6.1) for optimization (R Core Team, 2019). We ensured that all the maps were in the same projected coordinates system before performing any spatial analysis.

Planning units

We created a grid with 0.25-degree resolution in ArcMap to divide the terrestrial area in the world into 245,508 planning units (approximately 28×28km at the equator but size varies according to coordinates). We intersected the planning units map with land cover map to get land cover data within each planning units. We excluded those planning units with land cover types not suitable for conversion to new cropland, including current cropland, water bodies, snow or ice, and artificial areas. Global land cover was obtained from the Climate Change Initiative Land Cover (CCI_LC) year 2014 map (Climate Change Initiative Land Cover Team, 2017). After the exclusions, there were 157,231 planning units left susceptible of being converted to cropland. These planning units spanned over 25 different types of land uses (see Supplementary Information Table S4). We then calculated the area available for conversion within each planning unit.

Biological data

The analysis used four types of biological data: a key biodiversity areas (KBA) map (BirdLife International, 2017) to represent biodiversity at the broader scale; a forest distribution map adapted from the CCI_LC map through combining several land cover types (see Supplementary Information Table S4); a protected area (PA) map (UNEP-WCMC, 2016) to show the distribution of the current reserve network; and an intact habitat map derived based on human footprint maps (Venter et al., 2016).

We intersected the KBA map with the planning units map to derive the area of KBAs that overlapped with each planning unit. We also calculated the area of forest in each planning unit through spatially intersecting the maps. Intact habitats were defined as areas without presence of any of the eight individual human pressures considered in the human footprint assessment (Allan et al., 2019) (see Supplementary Information table S5).

Anthropogenic data

We selected three anthropogenic variables to describe human needs on nature: human crop demand, crop production, and agricultural rents. We considered the 17 globally most important crops based on their economic importance and area of production (banana, beans, cassava, cocoa, coconut, coffee, cotton, cowpea, groundnut, maize, millet, oil palm, rice, sorghum, soybean, sugarcane, and wheat) (Leff et al., 2004; Phalan et al., 2013). In total, these crops accounted for around 65% of total global crop production in year 2016 (FAO, 2017). We obtained projected human demand for each of the 17 crops by the year 2030 (the timeline for the SDGs) under business-as-usual scenario from the Food and Agriculture Organization of the United Nations (FAO) projections (FAO, 2018). Maximum crop production in each planning unit of each crop was based on crop potential yield (International Institute for Applied Systems Analysis, 2015). The potential production in each planning unit, if converted to cropland, was then obtained by multiplying the potential yield with the area available for conversion within each planning unit.

We calculated net annual agricultural rents (*AR*) for each crop *j* in each planning unit *i* as follows:

$$AR_{ij} = (p_j y_{ij} - w_i l_{ij} - r_i u_i k_i - trans_{ij}) \times a_i \qquad (1)$$

where *p* is the crop price (\$/ton), *y* is the crop potential yield (ton/ha·year), *w* is the labor wage (\$/day), *l* is the person-days to produce the crop (days/ha·year), *r* is the price of the tractor at the time of purchase (\$/tractor), *u* is the proportion of the tractor life span in one year of use, *k* is the quantity of capital input required (tractor/ha·year), *trans* is the transportation cost to transport the crop from farm to the market (\$/ha·year), and *a* is the conversion available area of each planning unit (in ha). Tractor cost is used as a proxy of capital cost for agricultural production, for which we assumed life span of 10 years with costs annualized to get the annual depreciation in capital asset value. Details of agricultural rent calculation were presented in the Supplementary Information.

Systematic sustainability planning model

We used the Gurobi package in R to identify the best allocation patterns for new cropland spatially. Gurobi uses several algorithms, including simplex and branch and bound, to solve integer linear programming problems and is guaranteed to find the optimal solution if enough time is given. Therefore, it always produces the same spatial solution for a given set of inputs to meet the specified targets in our formulation. In this study, we used it to find an optimal new cropland allocation by maximizing an objective function where both conservation needs and human food demands were considered as constraints.

The optimization problem maximized the amount of agricultural rent (AR) earned from all N planning units. This optimization was subject to ensuring the loss of each of K conservation features below certain thresholds (T_k) (i.e. a certain amount of each conservation feature was retained). In addition, it required enough crop production to satisfy future agricultural demand (d) for each of J crops:

$$\text{maximize} \quad \sum_{i}^{N}\sum_{j}^{J} AR_{ij} x_{ij}$$

$$\text{subject to} \quad \sum_{i}^{N}\sum_{j}^{J} r_{ik} x_{ij} \leq T_k , \quad \forall k \in K,$$

$$0.9 d_j \leq \sum_{i}^{N} s_{ij} x_{ij} \leq 1.1 d_j , \qquad \forall j \in J,$$

$$\sum_{j}^{J} x_{ij} \leq 1, \qquad \forall i \in N,$$

$$x_{ij} \in \{0,1\} \qquad (2)$$

where x_{ij} is a binary variable and represents whether planning unit i is allocated to crop j ($x_{ij}=1$) or not ($x_{ij}=0$). AR_{ij} is the agricultural rent generated by converting a planning unit i)to crop j (see eqn. 1) and r_{ik} measures the loss of each conservation feature due to the conversion. We used s_{ij} to represent production quantity of crop j in planning unit i. We allowed a $\pm$ 10% divergence from the actual demand to facilitate finding an approximate solution. We assumed that only one crop would grow in each planning unit after the conversion, occupying the entire area available for conversion. This is enforced by the third and fourth constraints.

Species extinction estimation

We estimated possible endemic bird and mammal species extinction rate due to projected new cropland allocation according to the countryside species-area relationship (SAR) model (Chaudhary et al., 2015; de Baan et al., 2013). It was limited to birds and mammals due to data paucity for other taxa.

$$S_{lost,g,e} = S_{org,g,e}\left[1-\left(\frac{A_{new,e}+\sum_{l=1}^{L} h_{g,l,e}\times A_{l,e}}{A_{org,e}}\right)^{z_e}\right] \quad (3)$$

where $S_{lost,\,g,\,e}$ is the number of species loss of taxa *g* due to new cropland allocation in ecoregion *e*, $S_{org,\,g,\,e}$ is the original number of species that would have occurred in natural habitat area $A_{org,e}$ in the ecoregion *e*, $A_{new,e}$ is the remaining natural habitat area after projected cropland allocation, $A_{l,e}$ is the updated area of each land use type *l* in each ecoregion, z_e is a constant assigned to each ecoregion, and $h_{g,l,e}$ is the affinity of each taxa *g* for land use type *l* in ecoregion *e*. It was calculated based on the local land occupation characterization factor $CF_{loc,g,le}$ as,

$$h_{g,l,e} = (1-CF_{loc,g,le})^{1/z_e} \quad (4)$$

We obtained $CF_{loc,g,le}$ and z_e data from previous studies by de Baan et al. (2013) and Chaudhary et al. (2015). We mapped area of each land use type before and after new cropland allocation based on the human land use map from Ellis and Ramankutty (Climate Change Initiative Land Cover Team, 2017). We got endemic species richness data for each ecoregion from WildFinder (World Wildlife Fund, 2006) and World Wildlife Fund provided the ecoregion distribution data (Olson et al., 2001).

Scenarios

We considered four different scenarios with various possible conservation targets to investigate how they influence new cropland allocation patterns (Table 1).

Scenario	Yield gap closure	PA conversion	KBA conversion	Conservation features	Scale of target application
Baselines					
I. (Close yield gap first, unconstrained expansion)	Yes	Yes	Yes	NA	Global
II. (Do not close yield gap first, unconstrained expansion)	No	Yes	Yes	NA	Global
Forest conservation					
I. (Globally coordinated)	Yes	No	No	Forest	Global
II. (Nationally constrained)	Yes	No	No	Forest	National

Table 1. Description of each scenario settings. Additional conservation scenarios are included in the supplementary information.

Baseline I: Existing cropland was intensified to produce the maximum yield before allocating new cropland. New cropland could be allocated anywhere as long as current land cover types are suitable for agricultural production.

Baseline II: Existing cropland was not intensified and produce at the current production levels before allocating new cropland. The other conditions remained the same as in the baseline scenario.

Forest conservation I: We added forests as a conservation feature and required that the overall loss of forests to be less than 5% of the total global forest area. We also did not allow conversion of any PAs. The other conditions remained the same as in the baseline scenario.

Forest conservation II: The conservation threshold in this scenario was set for each individual country instead of considering the world as a whole. Therefore, every single country needed to ensure loss of forests in their country boundary to be less than 5%. The other conditions remained the same as in the global forest conservation scenario.

Besides the abovementioned four scenarios, under the precondition of yield gap closure, we ran four additional conservation scenarios (PA exclusion, biodiversity conservation, intact habitat exclusion, and ecoregion habitat conservation) to explore optimization outcomes under different contexts. Moreover, under the precondition of no yield gap closure (maintaining current production level), we ran six pairing scenarios (PA exclusion, biodiversity conservation, intact habitat exclusion, forest conservation I, forest conservation II, and ecoregion habitat conservation). All of them are presented in the Supplementary Information.