Title: Proactive Policies Could Prevent Biodiversity Habitat Losses to Agricultural Expansion

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The projected loss of millions of square kilometres of natural ecosystems to meet future demand for food, animal feed, fibre, and bioenergy crops could massively escalate threats to biodiversity. Preventing this requires a detailed knowledge of how and where such threats are likely to be greatest. We developed a flexible approach to modelling future agricultural expansion based on observed historic changes, and combined this approach with species-specific habitat preferences for 19,859 species of terrestrial vertebrates. We project that 87.7% of species will lose habitat to agricultural expansion by 2050, including 1,280 species projected to lose >25% of habitat. Proactive policies targeting how, where, and what food is produced could reduce these threats, with a combination of approaches potentially preventing almost all these losses while contributing to healthier human diets. As international

biodiversity targets are set to be updated in 2020, these results highlight the importance of proactive efforts to reduce demand for agricultural land to safeguard biodiversity.

Main text

Biodiversity declines are accelerating across the world[1–3], with one fifth of terrestrial vertebrates threatened with extinction (categorised by the International Union for the Conservation of Nature, IUCN, as Vulnerable, Endangered, or Critically Endangered[4]). Habitat loss, driven by agricultural expansion, is the greatest threat to terrestrial vertebrates[5,6]. If current agricultural trends continue, pressures on biodiversity will increase substantially: projections based on population growth[7] and dietary transitions estimate the need for 2-10 million square kilometres of new agricultural land, largely cleared at the expense of natural habitats[8–11]. In the face of these agricultural trends, conventional conservation approaches, such as site based conservation, may be insufficient to conserve biodiversity[12,13]. Additional proactive approaches that reduce the underlying threats to biodiversity—such as agricultural expansion— will likely be needed to complement existing efforts[5,14].

Responding to the impending biodiversity crisis requires decisions based on high resolution, spatially explicit and species-specific assessments to identify the species and landscapes most at risk from future agricultural expansion. Results from these assessments help plan appropriate conservation responses—such as species- or location-specific legislation—and to assess which proactive changes to food systems have the greatest potential to reduce future threats to biodiversity before they occur. The utility of existing analyses for conservation planning and action has been limited by coarse spatial resolutions; a focus on a relatively small suite of species or on generalized biodiversity metrics such as species richness; or using narrative pathways that are neither tied to current agricultural trajectories nor are able to examine how specific changes to food systems might mitigate future biodiversity declines[5,12,15,16] (see Methods).

We address limitations of existing analyses by developing a model framework that increases the breadth and specificity of analyses, as well as their applicability to conservation efforts (Supplementary Figure 1). We analyse the impacts of agricultural expansion on an unprecedented number of species (almost 20,000) while explicitly accounting for differences in how individual species respond to agricultural land-use change, at a high spatial resolution (1.5 x 1.5 km), and by analyzing how proactive food system transitions might mitigate future biodiversity declines. In total, these changes enable us to identify the species and landscapes most at risk from agricultural expansion under current trajectories, as well as how proactive agricultural policies could reduce these threats.

Future patterns of agricultural expansion under Business-As-Usual

We developed a new, flexible, and high-resolution approach to modelling agricultural land cover change. Our approach is built on observed empirical relationships between historical changes in agricultural land cover and known correlates of agricultural land cover change (see Methods, Supplementary Figure 2). This differs from the approaches employed by global food system models such as IMAGE, MAgPIE, or GLOBIOM, which are based more on economic theory than on empirically observed patterns and changes. Our projections thus allow the exploration of agricultural futures at high spatial resolutions that are derived from observed trends, and can thus incorporate factors which are not accounted for in economic theory (for example strong or weak enforcement of protected areas, or the non-economic factors that determine agricultural expansion) and also be readily updated as new land cover data become available. To achieve this, we developed a flexible, spatially explicit, land allocation model at a resolution of 1.5 x 1.5 km using observed changes in agricultural land cover from 2001-2013 and spatially-explicit data on key determinants of land-cover change:

the suitability of an area for agricultural production[1], current agricultural land cover[17], previous changes in agricultural land cover[17], proximity to other agricultural land[17], market access[1], and the location of protected areas[1]. Specifically, we used satellite-derived historic land cover data[17] from 2002 to 2007 to fit region-specific multinomial models to estimate the probability that agricultural land cover increased, decreased, or remained the same from 2007 to 2012. Next, we used the same satellite data to fit region-specific generalized linear models to estimate the magnitude of any such change from 2007 to 2012.

We then paired this two-part land allocation model with country-level estimates of agricultural land demand at five year intervals from 2010 to 2050 derived from the EAT-Lancet global food system model[11] that accounts for domestic food demand and international patterns of trade. For each country and each time step, the land allocation model was first used to probabilistically select cells to experience a change in agricultural land cover extent, and then second to estimate the magnitude of this change. This process was repeated until a country's estimated agricultural land demand was met, and replicated 25 times to account for the probabilistic nature of the land allocation model. Because spatial patterns of agricultural expansion were consistent across model runs (see Supplementary Figures 3, 4 for variation across model iterations), we report results using the mean of the 25 model iterations.

Under Business-As-Usual (i.e. based on current trajectories), we projected a total increase in in global cropland of 26% or 3.35 million km^2. We projected particularly large increases in agricultural land throughout Sub-Saharan Africa (particularly tropical West Africa, the Rift Valley, and in the southern Sahel), South and Southeast Asia (particularly Bangladesh, Pakistan and southern Malaysia), and to a lesser extent Central and South America (large increases in northern Argentina, and much of Central America, smaller increases across southern Brazil) (Fig. 1, Supplementary Figure 5). These increases were driven by the EAT-Lancet model projecting income-dependent transitions towards diets that contain more calories and larger quantities of animal-based foods (Supplementary Figure 6), combining with high levels of projected population growth (Supplementary Figure 7) and low crop yields that are only projected to increase slowly (Supplementary Figure 8). In North America, our allocation model projected increases in agricultural land in south-central Canada and throughout the U.S. (but centered in the south-east). This was due to the EAT-Lancet model projecting increased demand for international exports, but a combination of lower projected population increases than in Sub-Saharan Africa, South and Southeast Asia and Latin America and higher crop yields led to smaller projected increases in agricultural land (Fig. 1, Supplementary Figure 5). In contrast, we projected reductions in agricultural land demand across eastern Europe and central and northern Asia (especially in Southern Russia and Eastern Belarus) due to small dietary changes projected by the EAT-Lancet model, combined with low or negative rates of population growth and high or increasing crop yields (Fig. 1, Supplementary Figures 5-8).

Our approach offers an empirically derived complement to integrated assessment models such as GLOBIOM [18], MAgPIE[19] and and IMAGE[20]. Despite the difference in modelling approaches, our projections are in broad agreement with those based on Shared Socioeconomic Pathways, with the exception of projected agricultural expansion in North America, which is not seen under all of the Pathways(*19*). This difference results from increased crop demand from the EAT-Lancet projections we used(*11*) and are in agreement with analyses based on other non-SSP projections(*20*). However, our projections are at a higher resolution than most existing efforts, while the modular and adaptable nature of the land allocation model means it can be updated as new data becomes available, and can be paired with any estimate of future agricultural land demand at local to global scales (see Supplementary Figure 1 for model construction).

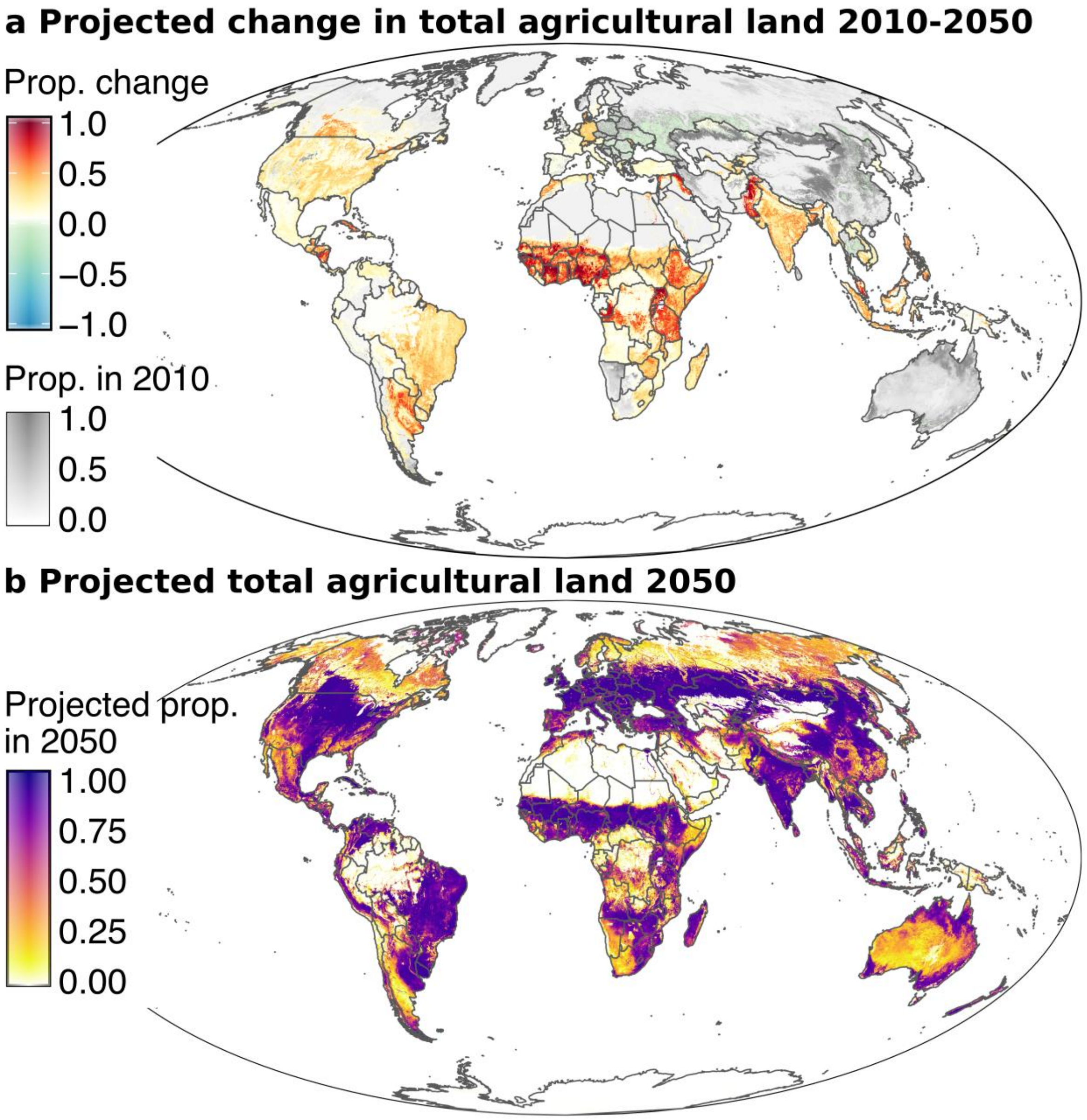

Figure 1. Projected extent of agricultural land in 2050 under Business-As-Usual a *Projected change in the proportion of agricultural land (cropland plus pastureland, in colour) in cells from 2010-2050, overlaid on proportions of agricultural land in 2010 for cells not projected to experience a change in extent (in greyscale). Note the offset scale to highlight areas with small decreases in the proportion of agricultural land.* ***b*** *Projected proportion of agricultural land in cells in 2050.*

Linking Business-As-Usual agricultural expansion to habitat losses

We next estimated changes in habitat area[21] for each of 4,003 amphibian, 10,895 bird, and 4,961 mammal species. To do so, we overlaid our projections of future agricultural cover with maps of current habitat for each species[22–24], using species-specific assessments of whether each species can survive and reproduce in agricultural land[4] to calculate changes in total area of habitat for each species (see Methods). We acknowledge that, because a species' population density will vary across its available habitat due to differences in climate, land cover, or land-use intensity[16,25], habitat loss may not linearly equate to population change.

In the Business-As-Usual scenario, we projected that 87.7% of species (17,409 species) would lose some habitat by 2050, 6.3% to have no change in habitat area, and 6.0% to have an increase in habitat area due to their survival in agricultural land, with 72.9% of these (877 species) being birds. If natural habitats are allowed to regrow in abandoned agricultural land, these numbers are projected to be 76.1%, 6.1%, and 17.8%, respectively, with considerable benefits for some species (Supplementary Data 1). Henceforth, we report results assuming that habitats do not recover in abandoned agricultural land within the time period we analysed, although our overall conclusions do not differ if we alter this assumption (Supplementary Data 1). We projected a mean loss of 5.8±0.1% of habitat across all 19,859 species in the analysis (range: 100% loss to 78.2% increase); across species losing habitat, this value was 6.7±0.9%, but with considerable variation between regions and species (Fig. 2). Projected mean habitat losses were greatest in Sub-Saharan Africa (14.4±0.3%% across all species) with particularly large losses for amphibians in Equatorial West Africa (where five ecoregions had projected mean losses of over 25%, and 10 ecoregions with mean losses over 20%, Supplementary Table 4) and for mammals in East Africa (eight ecoregions had projected mean losses over 18%, Supplementary Table 4). Large mean habitat losses were also projected in the Atlantic Forest in Brazil, in Eastern Argentina, across Central

America and the Caribbean, and in parts of South and Southeast Asia (Fig. 2, Supplementary Table 4).

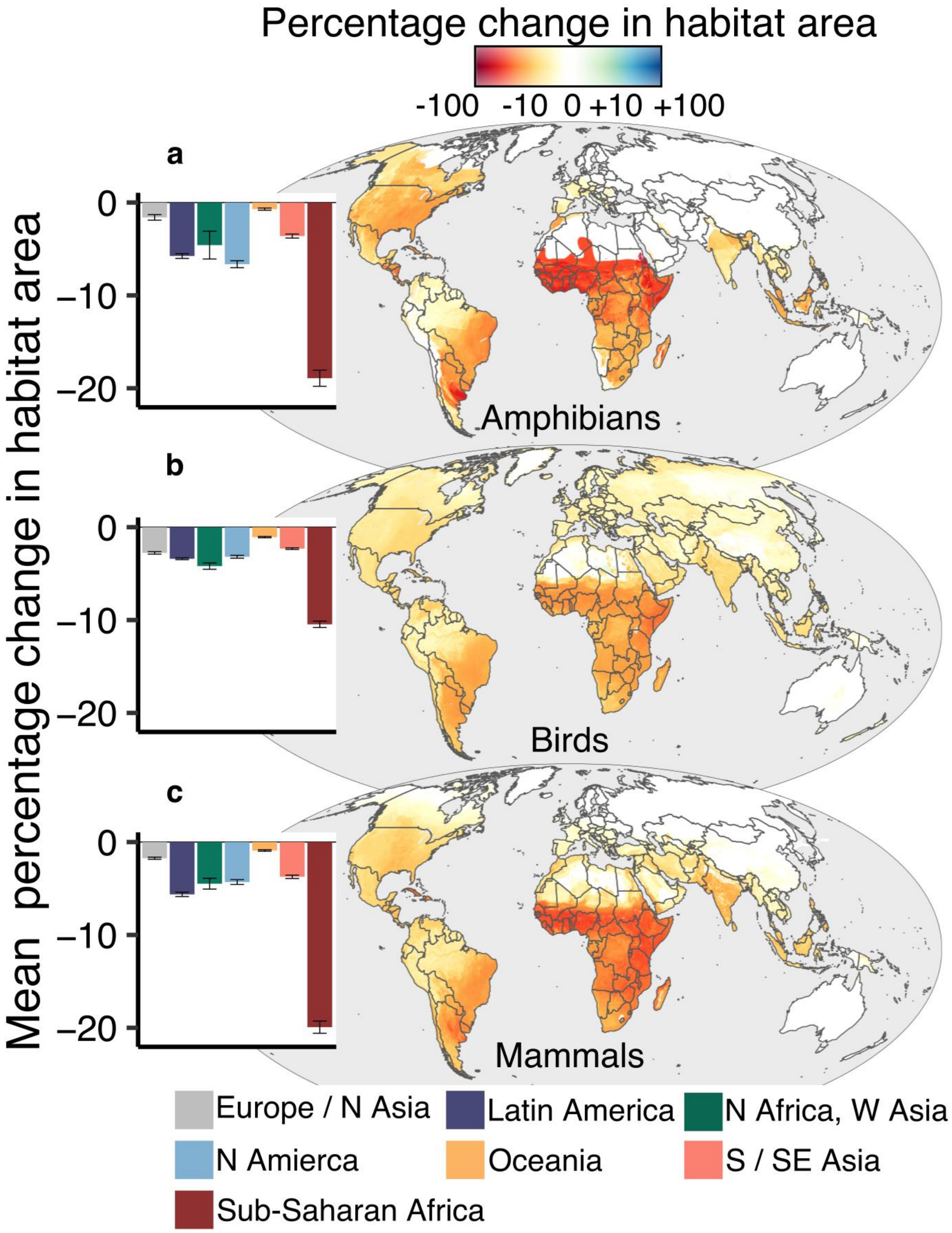

***Figure 2. Projected changes in habitat area in 2010-2050 under Business-As-Usual conditions** for **A** amphibians **B** birds **C** mammals. Maps show the mean change in habitat*

area for all species within a cell, with values on a log10 scale. Insets show the mean change in habitat area for all species within a region. See Supplementary Data 2 for which countries are included in each region.

Mean values conceal the severity of projected habitat losses for many species. By 2050, 1,280 species were projected to lose at least 25% of their habitat area (Fig. 3a) and will likely be at increased risk of global extinction. Of these species, 980 are not currently classified as globally threatened according to the IUCN and so may not be a primary focus of current conservation efforts. More alarmingly, 347 species were projected to lose at least 50% of their remaining habitat; 96 at least 75%; and 33 at least 90%. A high proportion of these heavily impacted species are currently listed as globally threatened with extinction (34%, 52%, and 55%, respectively), strongly suggesting that agricultural expansion could lead to regional or global extinction of many species in the coming decades. This highlights the need for analyses that project how and where future threats to biodiversity are likely to emerge, allowing conservationists and policy-makers to act proactively to mitigate against threats.

Overall biodiversity impact will be greatest where high rates of habitat loss coincide with large numbers of species (Supplementary Figure 9). Loss of total habitat area—the mean habitat loss within a cell multiplied by the number of species present—as well as the number of species losing at least 25% of their habitat were projected to be highest in Sub-Saharan Africa, particularly the Rift Valley and throughout tropical Western Africa (Fig. 3b, c). In Sub-Saharan Africa 22.5% of species (941 species: 179 amphibians, 406 birds, and 356 mammals) were projected to lose at least 25% of their remaining habitat, with 44 out of 52 Sub-Saharan African countries containing at least 25 such species (Supplementary Data 7). Projected habitat losses were also high in Latin America, particularly southeast Brazil and the remaining Atlantic Forest, with 246 species, including 99 amphibians, projected to lose at least 25% of their habitat (Fig. 3b). Our results highlight the disproportionate share of local, regional, or even global extinctions that Sub-Saharan Africa and Latin America are projected to account for, containing 93% of the species projected to lose ≥25% of their remaining habitat. These continent-wide patterns of habitat loss could radically transform ecosystems that hold a large proportion of the world's biodiversity, particularly of large mammals (in Sub-Saharan Africa) and birds and amphibians (in Latin America)[1].

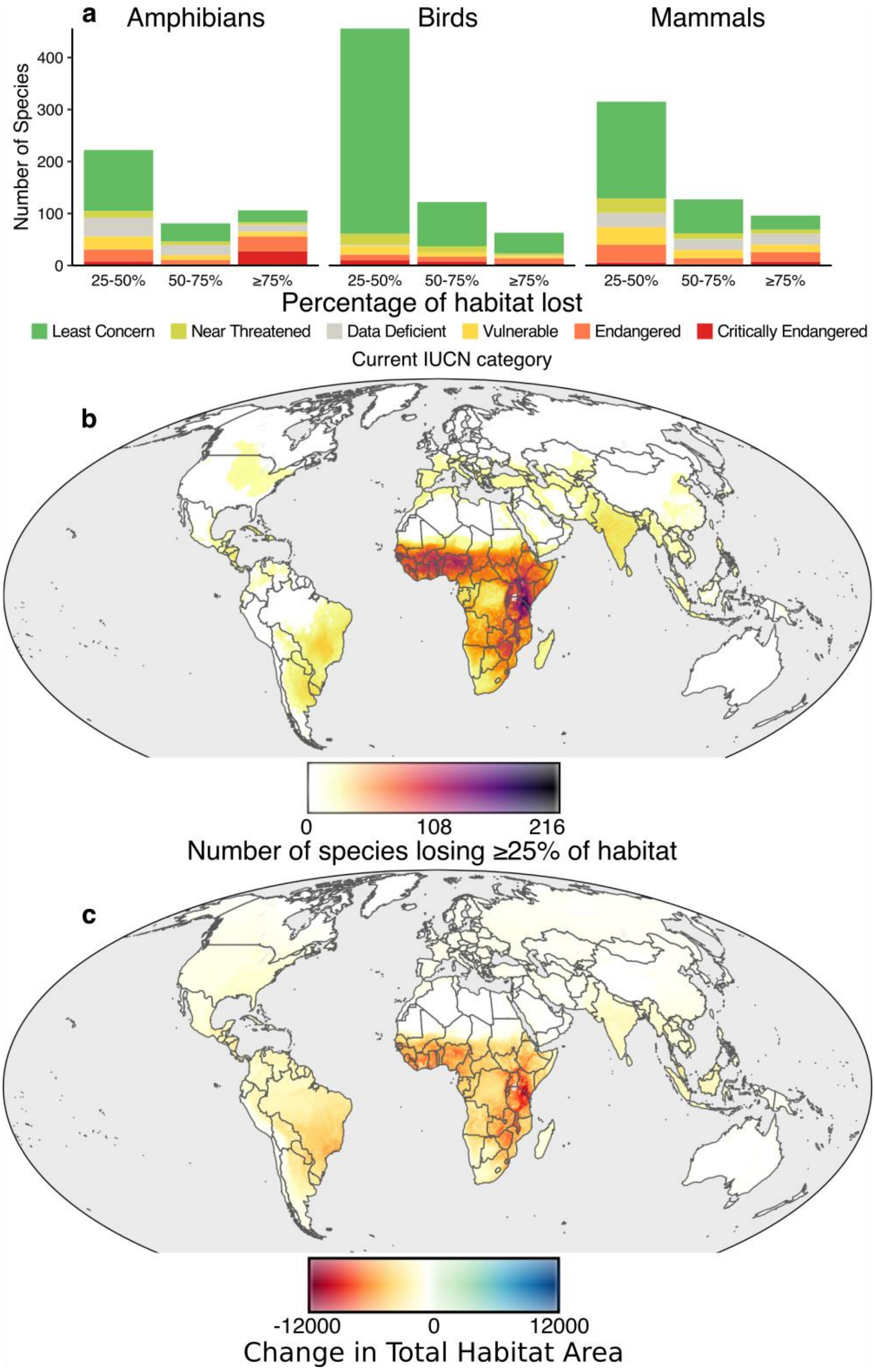

***Fig. 3. Severity of projected habitat losses from 2010-2050 A** Number of species projected to lose ≥25% of their 2010 habitat by 2050, split by current IUCN status **B** Global distribution of species projected to lose ≥25% of their 2010 habitat by 2050 **C** Projected changes in total habitat (mean habitat loss in a cell multiplied by the number of species present) by 2050.*

We projected small decreases in agricultural land in parts of Europe, Central and Northern Asia, China, Australia, and New Zealand (Fig 1a). If these lands are allowed to revert to a natural state— a process which may take decades or over a century[26]—then there is the possibility for small increases in habitat area in these regions. However, these potential increases for some species were far outweighed by projected losses in habitat area for others, and allowing for recovery after habitat regrowth and restoration has a minor impact to the overall projections of widespread habitat loss across all species examined (Supplementary Data 1).

Proactive changes to food systems to reduce threats to biodiversity

The projected severity of agricultural land cover change on habitat area means that proactive policies to reduce future demand for agricultural land will likely be required to mitigate widespread biodiversity declines. To investigate the potential of such a proactive approach, we developed a "Sustainable Food Systems" scenario that implemented four changes to food systems: a global transition to healthier diets; halving food loss and waste; closing crop yield gaps; and global agricultural land-use planning to avoid competition between food production and habitat protection. In addition, to identify the relative impacts of specific changes to the food system, we investigated the impacts of each approach individually. We used previously published scenarios for diets, food waste, and yield increases[5,11], and used projected habitat losses in the Business-As-Usual scenario to identify the countries that could most benefit from global agricultural land-use planning. In each case, we assumed each approach was steadily adopted, such that the complete transition was only achieved in 2050 (see Methods for details).

Under the Sustainable Food Systems scenario, we projected that all regions would see mean habitat losses of 1% or less by 2050 (Fig. 4): that is, with global coordination and rapid action, it should be possible to provide healthy diets for the global population without major habitat losses. The greatest benefits compared to Business-As-Usual were in Sub-Saharan Africa, where we projected a mean loss of habitat of 1.0±0.04% under Sustainable Food Systems compared with a mean loss of 14.4±0.3% under Business-As-Usual (Fig. 4, Supplementary Figures 10, 11). If natural habitats are allowed to regrow in abandoned agricultural land, then we projected mean habitat increases in every region (Supplementary Data 1).

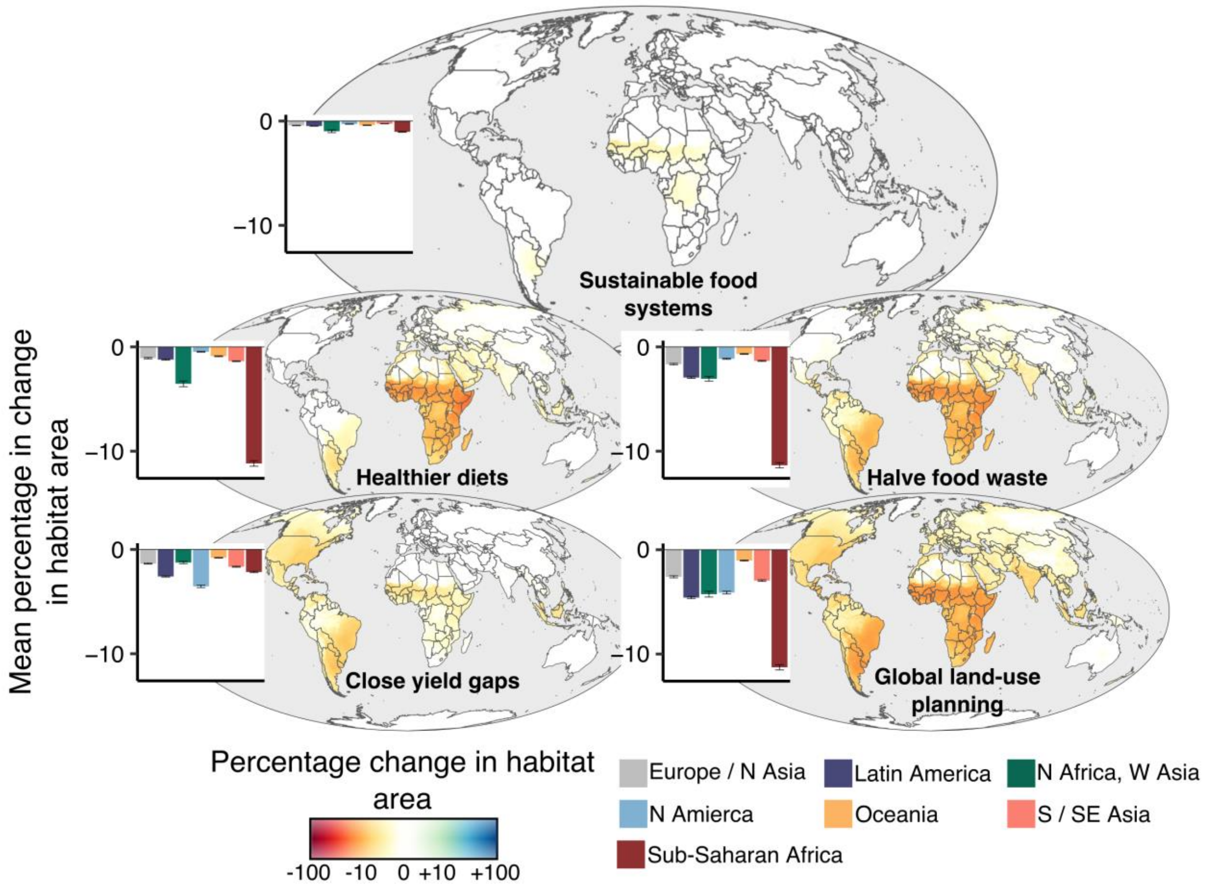

Figure 4. Projected changes in mean habitat area from 2010-2050 under alternative scenarios. *Maps show the mean change for all species of all taxa in a cell, with values on a log10 scale. Insets show the mean change in habitat area for all species within a region. The lower four panels show the results from scenarios using single approaches, the top panel ("Sustainable food systems") show the combination of all four approaches. See*

Supplementary Data 2 for which countries are included in each region. Patterns for total habitat are similar (Supplementary Figure 12).

Perhaps more importantly, habitat losses were far less severe for the species most heavily impacted under business-as-usual. Globally, only 33 species were projected to lose more than 25% of their habitat, compared to 1,280 under Business-As-Usual. Thus, our analyses demonstrate that addressing the underlying drivers of agricultural expansion has the potential to greatly benefit the most at-risk species, thereby reducing extinction risks. However, the majority of species (81.6%) were still projected to lose small amounts of habitat, suggesting that conventional conservation measures will continue to be vital to protect biodiversity.

The impacts of individual approaches varied regionally. Closing yield gaps was projected to have the largest overall benefits (Fig. 4) and was particularly effective in North Africa, West Asia, and Sub-Saharan Africa where large yield gaps remain[27,28]. Under this scenario only 33 species in these regions were projected to lose more than 25% of their habitat, compared to 953 under Business-As-Usual. Projected benefits were considerably lower in other regions, where yield gaps are smaller, but still reduced the number of such species from 361 to 103. The magnitude of these projected benefits supports, and is supported by, recent analyses investigating the land-saving potential of closing yield gaps across the world[1,2] Transitioning to healthier diets and reducing food waste had considerable benefits—while not completely eliminating habitat losses—particularly in wealthier regions with high per capita consumption of both calories and animal-based foods, and in regions such as South America with high consumption of animal-based foods (Fig. 4). In contrast, projected benefits from international land-use planning were far smaller, with 1,026 species being still projected to lose at least 25% of their habitat. The biggest benefits were projected in Sub-Saharan Africa, where all the countries with reduced agricultural land demand under this scenario were located, but even here there were 646 such species (compared to 942 under Business-As-Usual, 673 under healthy diets, and 695 under halved food waste). By analyzing the potential benefit of individual food system changes, we found that combining different approaches had synergistic benefits. For example, a country projected to see a 20% fall in food demand under the halved food waste scenario and a 50% increase yields under the close yield gaps scenario would see 20% and 33% reductions in land demand under each scenario respectively, compared to Business-As-Usual. However, when combined, the area required falls even further, to just 53% of Business-As-Usual demand. This results in the avoided habitat loss under Sustainable Food Systems being greater than the sum of the avoided loss under the four constituent scenarios (Fig. 4).

Conclusions: Maintaining biodiversity in a world with 10 billion people

Our projections suggest that under business as usual agricultural expansion will continue to drive widespread and severe biodiversity declines, but that these could be avoided with concerted efforts to address food consumption and production as ultimate drivers of biodiversity loss. Our approach and results are immediately relevant to international efforts for the development of new strategic goals and targets for 2030 and 2050 under the auspices of the Convention on Biological Diversity. We identify which policy approaches have the greatest potential to combat the underlying drivers of future biodiversity declines in different countries and highlight, at spatial scales relevant to conservation action, the species and landscapes most at risk. These results can support proactive planning of both changes to the wider food system, and on-the-ground conservation schemes to mitigate threats.

Our approach offers an empirically derived complement to integrated assessment models such as GLOBIOM [18], MAgPIE[19] and and IMAGE[20]. Despite the difference in modelling approaches, our projections are in broad agreement with those based on Shared Socioeconomic Pathways, with the exception of projected agricultural expansion in North America, which is not seen under all of the Pathways(*19*). This difference results from increased crop demand from the EAT-Lancet projections we used(11) and are in agreement with analyses based on other non-SSP projections(20). Our projections are at a higher resolution than most existing efforts, while the modular and adaptable nature of the land allocation model means it can be updated as new data becomes available, and can be paired with any estimate of future agricultural land demand at local to global scales (see Supplementary Figure 1 for model construction). The adaptable and updateable nature of our approach offers particular improvements when accounting for non-linearities in agricultural expansion. For example, a new road being built or the removal of a protected area could lead to rapid agricultural expansion in a region that neither our approach nor integrated assessment models highlight as vulnerable. Our approach, however, allows for the rapid inclusion of these changes into projections by adjusting the value of explanatory variables (in these cases travel time and the presence of a protected area) and recalculating the probability of future agricultural expansion. Thus, we hope that our approach can help provide a dynamic and responsive tool for decision makers to investigate the potential impacts of different policies.

Future human activities will likely have even greater impacts on biodiversity than those projected by our scenarios. Anthropogenic climate change is likely to drive widespread changes in ecosystems both directly, through impacts on species' potential distributions[1] and indirectly, by affecting agricultural yields[1] and the relative suitability of different regions[1]. Uncertainty in how changing precipitation and temperature regimes might affect farmer profitability, and thus the future location of agricultural lands, preclude a quantitative assessment of the impact of climate change on biodiversity. Likewise, increasing agricultural yields—the proactive approach estimated to have the largest potential benefits for reducing global habitat loss—may also have negative consequences not accounted for in this analysis. Increasing crop yields—even if sustainably—often has negative biodiversity consequences for species which exist in or near agricultural lands. As such, all scenarios will likely see a decline in habitat suitability (and thus biodiversity) on cropland, an effect that is likely to be exacerbated if yield gaps are closed. Other human impacts, such as the habitat fragmentation that accompanies land clearing; over-hunting; invasive species; and pollution also threaten biodiversity[5,6,31,32]. However, the proactive changes to the global food system that we discuss could also help reduce these threats. For example, reducing demand for new cropland would reduce habitat fragmentation, reduce greenhouse gas emissions from land-use change, and lessen the opportunity costs of protected areas for local people[33], thus increasing protection from hunting.

Here, we demonstrate the potential benefits of actions covered under our ‘sustainable food system’ to conservation, but such recommendations remain a long way from specific policy recommendations. Actions will require locally appropriate policies, taking into account individual countries’ socio-economic and governance environments, the cultural acceptance of different strategies, and on-the-ground capacity to implement strategies. Past successes can provide insights into how to ensure that strategies are both effective and maintain fair and equitable access to food, for example, through increasing crop yields[34–36], shifting to healthier dietary patterns[37–39], reducing food and crop waste[40,41], and implementing landscape-scale land-use planning[42]. Previous efforts to increase sustainability can also be used to avoid unintended consequences, such as when increases in agricultural yields promote local agricultural expansion[43].

Completely achieving the sustainable food systems we investigated may not be feasible in all situations, but there will likely be benefits of even the partial implementation of these approaches. As we approach the updating of the Convention on Biological Diversity’s targets for global biodiversity conservation, now in 2021, and the halfway point of the SDGs in 2022, our results strongly suggest there are synergies between biodiversity conservation and sustainable development. The approaches we investigated will also be key to meeting other

SDGs: in particular raising reducing food waste, and shifting to healthier diets supports Goals 2 (“No hunger”), 3 (“Good health”), and 12 (Sustainable consumption), but also economic and social development (Goal8, “Good jobs and economic growth”) and climate action (Goal 13, “Climate action”), bringing further benefits to people, biodiversity, and the wider environment **REFs**. These efforts to change how we produce and consume food will be a challenge, but one which cannot be avoided if we are to safeguard species for future generations.

Methods

To project impacts of future agricultural land-cover change on biodiversity, we linked a land demand model, a land allocation model, and a biodiversity model in a flexible framework (Supplementary Figure 1). This approach to be readily adapted, for example to different future scenarios or different spatial scales, or to incorporate new data as it becomes available. Collectively, this approach enables us to project changes in land cover and their impact on habitat availability for individual species at a resolution of 1.5 x 1.5km for every 5 years from 2010 to 2050. Our analysis includes nearly 20,000 species of birds, mammals, and amphibians, and 152 nations that occupy >99% of Earth’s ice-free land and contain >99% of current agricultural land (see Supplementary Data 2). Full details of model specification, datasets used, and sensitivity analyses are in Supplementary Information.

Land Demand Model

Projections of agricultural land demand under Business-As-Usual

We used income-dependent projections of country-specific agricultural production under Business-As-Usual conditions (i.e. continuing historic trajectories) from EAT-Lancet Commission[11], pairing them with the United Nation’s medium-fertility population projection[65,66] and previously published yield projections[1]. We did not use the population projections used in EAT-Lancet because they are derived from Shared Socioeconomic Pathway (SSP) scenarios[64] and so are not updated to account for recent population trends. As such, SSP 2—the pathway most similar to current Business-As-Usual trajectories—projects approximately 570 million fewer people worldwide than current UN medium variant population projections[1]. Additionally, we did not use the yield scenarios from the EAT-Lancet projections because they assume increases in future crop yields at faster-than-historic trajectories[11], which is not been supported by historic data[1]. We instead used published crop yield forecasts that project crop yields increase along historic linear trajectories, but cannot surpass current country-specific maximum potential yields[1–3].

We projected cropland demand for each country in each 5-year time period from 2010 to 2050. To do so, we divided projections of demand for national food production (derived from combining EAT-Lancet projections with UN population projections) by crop yield projections. EAT-Lancet estimates of current cropland are based on FAO data[1], while the Land Allocation Model is based on MODIS satellite data [1]. We therefore harmonised EAT-Lancet projections with satellite data by: (1) calculating proportional change in cropland in each 5-year time period (here called a “5-year target”) from 2010-2050; (2) estimating the total cropland in each country in 2010 based on MODIS data; (3) multiplying this satellite-derived estimate by the projected change in proportional demand; and (4) capping country-specific land-demand projections at FAO estimates of potential arable land in each country[55]. This ensures continuity between datasets but could lead to under-projecting agricultural expansion in countries where cropland is under-detected by satellite data (e.g. very small areas are farmed, or farming is largely under dense tree cover).

We assumed the area of pastureland remained constant for each country, following recent patterns[55], reallocating pastureland within a country if cropland expanded into existing pastureland. See Supplementary Information for more details.

Projections of agricultural land demand under alternative future scenarios

To investigate the impact of proactive policies that could reduce future cropland demand we repeated the Business-As-Usual analysis with five alternative scenarios:

(1) **Healthy diets:** Diets transition from current diets to healthier composition and caloric quantity[11].

(2) **Halved food waste:** Food loss and waste throughout entire food supply chains is reduced from current rates[67] by 25% in 2030 and halved by 2050.

(3) **Close yield gaps:** Yields increase linearly from current yields to 80% of the estimated maximum potential by 2050. This upper bound was chosen as increasing yields above 80% often decreases economic profits[68].

(4) **International land-use planning:** Agricultural production shifts from the 25 countries projected to have the greatest mean losses of suitable habitat across all species to countries where less than 10% of species are threatened with extinction and less than 10% of species would qualify as being threatened with extinction under IUCN Criteria B2[1] under Business-As-Usual in 2050. The shift in agricultural production is gradual, such that an additional 10% of total food demand is imported by 2030 and by 20% in 2050.

The goal of this scenario is to estimate the impact on biodiversity of land use planning across international borders, avoiding expansion in the most at-risk countries. We recognize this scenario could be antagonistic to food security and sovereignty, especially in countries where agriculture is a large source of employment and/or income.

(5) **Sustainable food systems:** All four approaches were adopted simultaneously.

By 2050, each scenario individually—with the exception of international land-use planning—is estimated to reduce global demand for cropland by at least 2.5 million square kilometres, while simultaneous adoption of all four scenarios would reduce global land demand by ~7.5 million square kilometres. International land-use planning had smaller impacts, reducing global demand by 220,000 square kilometres. See Supplementary Information for more explanation on the alternative land demand scenarios.

Land Allocation Model

We developed a novel and highly resolute (1.5km x 1.5km) spatial allocation model using observed changes in land cover to project future spatial patterns of agricultural land-cover change. We fitted relationships between empirically observed changes in cropland or pastureland and a set of key explanatory variables and assumed that these fitted relationships remain constant into the future. Thus, we are not simply extrapolating past changes in agricultural land into the future, but rather basing projections on an understanding of the factors that shape how spatial patterns of agricultural land-cover evolves through time.

By separating projections of agricultural land demand from its spatial allocation, our approach enables investigation of how specific interventions might influence future land-use change and biodiversity loss. Our projections are at a far higher resolution than existing projections of agricultural land-use change, e.g. GLOBIOM (5-30 arc minutes; approximately 100-2500 km2 at the equator)[18], CLUMondo, and MAgPie (30 arc minutes; approximately 2500 km2 at the equator)[19,44]. This allows stakeholders to identify areas likely to experience large biodiversity declines at the spatial scales at which conservation actions and policies are implemented.

Modelling past changes in agricultural land

To understand past drivers of change in agricultural land we applied a two-stage modelling process applied to each 1.5 x 1.5 km terrestrial cell on earth. First, we fitted a multinomial regression to estimate the probability a cell experienced a change in the proportion of agricultural land during a 5-year period. Secondly, we fitted generalized linear models (GLMs) to estimate the magnitude of this change. We fitted separate models for cropland and pastureland because of differences in the relative importance of factors influencing their dynamics.

Data Inputs

Land-use change is driven by interacting biophysical and socio-economic forces[45]. We reviewed land-use change literature, identifying potential drivers of agricultural expansion and including those where global data was available at appropriate spatial resolutions. We therefore included in our models: extent and surrounding agricultural land; historic changes in agricultural land; agro-ecological suitability; travel time to large cities (>50,000 people) as a proxy for market access; and the presence of a protected area in a cell[1–7]. See Supplementary Information for more detail and data sources.

We resampled all data to 1.5 x 1.5 km Mollweide projection using the resample() function in the raster package[1] in R[1]. Note that agro-ecological suitability was originally at a coarser resolution[1] (Supplementary Table 2), adding a degree of uncertainty to our projections. All other input data was originally at a higher resolution.

Model fitting

We fitted region-specific multinomial regressions to estimate the probability that each cell experienced a change in cropland or pastureland extent and then used GLMs to estimate the magnitude of this change. Because drivers of cropland and pasture expansion differ by region

(Supplementary Data 3-6), we fitted separate models for each IUCN region[59] and for cropland and pastureland.

We *a priori* included the same explanatory variables for all models (although see Supplementary Table 2 for differences between cropland and pastureland models) and used cell-specific values for each explanatory variable.

Examining univariate relationships between explanatory and response variables showed non-linear relationships for some variables. We therefore log-transformed travel time and included quadratic effects for all variables except AES and presence/absence of a protected area. We also included country as a fixed effect in the model because differences in country-specific laws, policies, and demand for agricultural land affect the spatial pattern of cropland expansion. See Supplementary Information for more information on model fitting.

Probability of Change in Agricultural Extent

Our first response variable was whether the proportion of cropland or pastureland in a cell increased, decreased, or remained constant from 2007 to 2012. To account for uncertainty in MODIS data, we classified cells as having a constant agricultural extent if the proportion of a cell under agricultural land cover changed by less than 0.025 from 2007 to 2012. We then used the R package {nnet}[60] to fit a multinomial regression model to estimate the probability a cell increased, decreased, or did not change in cropland or pastureland extent from 2007 to 2012.

Magnitude of Change in Agricultural Extent

To estimate the magnitude of agricultural cover change in a cell, we fitted separate GLMs to cells that experienced increases in agricultural land and those that experienced decreases. This resulted in three GLMs for each IUCN region: cropland increases, cropland decreases, and pastureland increases. We did not fit models for pastureland decreases because we assume pastureland extent remains constant in each country. We fitted models using the glm() function in the {stats} package in R[61], with a gamma error distribution and a log-link function to bound estimates between 0 and 1.

Modelling results and accuracy

Model coefficients and accuracies are shown in Supplementary Table 3 and Supplementary Data 3-6. See Supplementary Information for more details on modeling testing, results and accuracy.

Modelling Accuracy: Probability of Change in Agricultural Extent

We assessed model accuracy by classifying cells as having expanded or contracted from 2007-2012 based on the cell's most probabilistic modelled outcome. We then compared these classifications with actual changes over 2007-2012.

Model accuracy varied across regions, ranging from ~62.5% (Caribbean) to ~95% (North Africa) for cropland and 59% (Oceania) to 77% (South and Southeast Asia) (Supplementary Table 3) for pastureland. This compares with a 33% chance of randomly selecting the correct outcome. The lower accuracy of pastureland predictions is possibly due to MODIS data not differentiating between natural grasslands or savannas and artificial pastures[17].

Agricultural Projections: Projecting the location and magnitude of future agricultural land cover change

We estimated the probability and magnitude of future agricultural land cover change for every cell using the coefficients from the fitted models. We extracted land cover data from MODIS for 2005 (estimated as the mean of 2004-2006) and 2010 (mean of 2009-2011), using 2010 as a baseline for our projections and calculating the change from 2005 to 2010 as an independent variable. We used the region-specific multinomial models to estimate the probability that each cell would experience an increase or decrease in cropland, then estimated the magnitude of these increases or decreases using the GLMs. See Supplementary Information for more detail on how the location and magnitude of future agricultural land cover change was projected.

Cropland expansion

To project future agricultural land cover we then linked these estimated probabilities and magnitudes of land-cover change from the Land Allocation Model with the agricultural land demand estimated from the Land Demand Model (Supplementary Figure 1).

For countries with a projected increase in cropland demand, we randomly selected a single cell, based on the probability it would experience an increase in cropland extent (i.e. the output from the region-specific multinomial model), then increased the proportion of cropland in the chosen cell by the cell-specific amount estimated from the expansion GLMs. We updated the estimates from both parts of the model (because the area of cropland is a key predictor), reduced the country's five-year agricultural land demand target by the amount of expansion estimated for the cell, and repeated the process until the country's five-year target for cropland was met.

For countries projected to see a decrease in cropland, we used the same procedure, but using the probability of cells experiencing a decrease in cropland from the multinomial model, and the estimated magnitude of this decrease from the contraction GLMs.

Changes in pastureland

Following recent trends in global pastureland[55,71] and the EAT-Lancet projections, we did not project changes in countries' areas of pastureland. However, we did allow cropland to expand into pastureland. This displaced pastureland was then reallocating within the country using the allocation process described above for crops, but using the region-specific models for pastureland and additionally assuming pastureland cannot expand into cropland. To avoid overestimating future pastureland extent, we limit pastureland expansion to cells identified as having livestock by Gridded Livestock of the World in 2010. If pastureland extent could not expand adequately to meet the five-year target, we assumed that shortfalls were compensated by livestock intensification[5,72].

Adjusting probabilities and the magnitude of changes

Agriculture cannot expand into all regions and land cover classes, specifically regions with very low growing degree days, and urban, rock and ice, barren ground, and water land cover classes. We therefore assumed that agriculture could not expand into certain cells based on their land cover type and climatic conditions, and further capped the potential amount of agricultural land based on the proportion of each cell that is suitable for agriculture. See "Input data for models" and "Adjusting probabilities and the magnitude of changes" in Supplementary Methods for details.

Consistency of projections

Because the land allocation model is probablistic, we repeated it 25 times, calculating the mean and standard deviation of the extent of cropland and pasture in each cell for each five-year time period and using the mean value in our analyses.

The allocation model produced consistent projections (Supplementary Figure 3). The median global coefficient of variation (standard deviation / mean) in 2050 was 0.26 for cropland and <0.001 for pastureland (Supplementary Figure 4), indicating variation in agricultural extent was small relative to estimated mean agricultural extent.

Potential impacts of climate change on agricultural land

We did not include the potential impact of climate change on AES or agricultural yields in our models. Doing so would rely on a large number of untestable assumptions over farmer and policy responses to environmental change, and is further hampered by a lack of consensus of how climate change might affect AES and crop yields. See Supplementary Information for a longer discussion of how climate change might affect future patterns of agricultural land cover change.

The flexibility and adaptability of our approach allows for the easy inclusion of climate change impacts in the future. This can be done by adjusting future yield projections based on local conditions and adaptive capabilities, or by adjusting future AES to capture how changing climates might affect the relative suitability of different regions.

Biodiversity Model

Current area of habitat

Maps of suitable habitat (referred to as Area of Habitat, AOH[21]) were produced for 4,003 amphibians, 10,895 birds, and 4,961 mammal species[21–24]. These maps were originally developed at 300 x 300m resolution through deductive habitat suitability models integrating species ranges with data on suitable land-cover and elevations[21]. These habitat models reliably predict species distribution over wide geographical and taxonomic extents at the 1-km resolution[23,24]. Supplementary Figure 9 shows the species richness patterns created from the AOH maps.

Species' habitat tolerances

We used IUCN data to define whether species are able to survive in agricultural land[1]. For each species, we recorded if habitats were "suitable" or "marginal" and took the maximum value of all habitats that qualify as either cropland or pastureland. i.e. if a species has "Arable Land" as "marginal" and "Plantations" as "suitable", we defined cropland as "suitable" for the species. See Supplementary Information for a longer description on species habitat tolerances.

Current Area of Habitat

We next estimated the global area of suitable habitat for each species in 2010. We first calculated the overlap between each species' suitable habitat and current cropland and pastureland (from MODIS data) and subtracted the area of agricultural land from the habitat maps, adjusting for suitability of cropland or pastureland: we assigned "suitable", "marginal", and "unsuitable" habitats a value of 0, .5, and 1, respectively, and multiplied this value by the overlap between habitat and agriculture in each cell. Thus, the value in each cell indicates the proportion of the cell suitable for a species. We then summed this value to estimate of area of suitable habitat in 2010. See Supplementary Information for more detail on how current area of habitat was calculated.

Biodiversity Projections

We estimated future changes in area of suitable habitat for 19,859 species of terrestrial amphibians, birds, and mammals, repeating the process described above for each 5-year time period from 2010 to 2050. We assumed species were unable to recolonise areas where agricultural land was abandoned to provide conservative estimates of biodiversity gains from agricultural abandonment. Altering this assumption such that species are able to colonise abandoned agricultural areas (as is often observed in long-term dynamics[80]) has little overall impact on our results: with recolonisation allowed, 17.8% of species were projected to see their area of habitat area increase, compared to 6.1% without recolonisation, and the mean change in habitat area for these species increased from 1.2% to 2.2% (Supplementary Data 1). Across all species, mean changes were even smaller, changing from a mean loss of 5.8% to a mean loss of 5.3% with recolonisation. Species for which agricultural land is suitable could see increases in area of habitat as cropland and pastureland expand, or as pastureland is converted into cropland.

Projecting changes in habitat extent under alternative scenarios

We repeated the process above for each of the five alternative scenarios and calculated both the absolute changes in habitat area, as well as the difference between Business-As-Usual and the alternatives.

References

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