One Earth

Article

Mapping human-nature archetypes to guide global biodiversity, food security, and land-use policy

Highlights

- We identify human-nature archetypes that share social-ecological characteristics
- Archetypes indicate opportunities and challenges to achieve global policy targets
- 23% of world's land area offers strong potential for nature conservation
- 48% of world's land area demands restoration and ecological intensification action

Authors

Diana Sietz, Aidin Niamir, Daniel Müller, Thomas Hickler, Keiichiro Kanemoto, Daniel Dean Moran, Kirsten Thonicke

Correspondence

diana.sietz@thuenen.de

In brief

The international community agreed on global policy targets for nature conservation, food security, and sustainable agriculture. Yet regional opportunities and challenges to achieve these targets remain insufficiently understood. We cluster the globe into 25 regions with similar social-ecological features that highlight areas with distinct opportunities for nature conservation, ecological restoration, and harnessing of ecosystem services for food security. Our findings help prioritize policy action that can underpin national biodiversity and land-use policies to more effectively achieve global targets.

Sietz et al., 2025, One Earth *8*, 101416
August 15, 2025
https://doi.org/10.1016/j.oneear.2025.101416

CellPress

One Earth

CellPress OPEN ACCESS

Article

Mapping human-nature archetypes to guide global biodiversity, food security, and land-use policy

Diana Sietz,[1,2,11,*] Aidin Niamir,[3] Daniel Müller,[4,5,6] Thomas Hickler,[3,7] Keiichiro Kanemoto,[8,9] Daniel Dean Moran,[10] and Kirsten Thonicke[2]

[1]Thünen Institute of Biodiversity, Thünen Institute, Federal Research Institute for Rural Areas, Forestry and Fisheries, 38116 Braunschweig, Germany
[2]Department of Earth System Analysis, Potsdam Institute for Climate Impact Research (PIK), Member of Leibniz Association, P.O. Box 60 12 03, 14412 Potsdam, Germany
[3]Senckenberg Biodiversity and Climate Research Centre, Frankfurt am Main, Germany
[4]Department Structural Change, Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Theodor-Lieser-Str. 2, 06120 Halle (Saale), Germany
[5]Geography Department, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany
[6]Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany
[7]Institute of Physical Geography, Goethe-University, Altenhöferallee 1, 60438 Frankfurt am Main, Germany
[8]Graduate School of Environmental Studies, Tohoku University, Aoba 468-1, Aramaki, Aoba-ku, Sendai 980-8572, Japan
[9]Research Center for Social Systems, Shinshu University, Matsumoto 390-8621, Japan
[10]IMPACT Department, NILU, Kjøpmannsgata 8, 7014 Trondheim, Norway
[11]Lead contact
*Correspondence: diana.sietz@thuenen.de

https://doi.org/10.1016/j.oneear.2025.101416

SCIENCE FOR SOCIETY Biodiversity, food, and agriculture are deeply interconnected, yet global policies often overlook important regional interlinkages and are hindered by sectoral silos. In December 2022, global decision makers committed to tackle ongoing biodiversity loss, food insecurity, and rising inequity with the Kunming-Montreal Global Biodiversity Framework (GBF). Food and agriculture are central to the GBF, as biodiversity is vital for food security and agriculture remains a major driver of biodiversity loss. Yet achieving the GBF's objectives will only be possible when all countries contribute effectively, reflecting their specific contexts. Our research supports this by mapping globally recurring patterns of people's interactions with nature, highlighting both opportunities and challenges. This helps international and national decision makers to tailor policy targets, such as GBF targets, to regional contexts and prioritize conservation, restoration, and sustainable farming actions where they are most needed.

SUMMARY

Reconciling biodiversity conservation, food security, and sustainable agriculture at global scale requires a clear understanding of regional social-ecological opportunities and challenges. This understanding helps untap regional contributions to better achieve global policy targets, such as those framed in the Kunming-Montreal Global Biodiversity Framework (GBF). Yet previous global syntheses of social-ecological interlinkages remain limited in thematic and spatial detail, restricting the discussion of regional contributions and targeted policy implementation. Here, we present 25 human-nature archetypes derived from clustering of global social-ecological data revealing regional opportunities and challenges for meeting global policy targets. Our results differentiate regions with large conservation opportunities from those well suited for ecological restoration or ecological intensification. They highlight the widespread need for improving governance to enhance food security and re-design agricultural systems. Overall, our analysis supports international and national decision makers in tailoring GBF targets to regional specificities in order to more effectively achieve global sustainability goals.

INTRODUCTION

In the 19th century, Alexander von Humboldt emphasized the close interlinkages between land use and ecosystems. He represented holism in science based on interacting natural and social processes.[1] Successfully translating these insights into policy advice was key to him to ensure progress in enhancing biodiversity, food security, and equity. Yet the subsequent disciplinary and sectoral fragmentation of science and policy[2,3] have ruled out essential aspects of Humboldt's holistic worldview, perturbing human-environmental relationships. As a result, biodiversity loss, hunger, and inequity accelerated,[2,4,5] clearly demanding targeted social-ecological research to strengthen a new vision of development that reflects the underlying interlinkages. Terrestrial biodiversity loss is primarily driven by land-use change including agricultural expansion, intensification, and specialization.[4,6] These processes contribute to the extinction threat of about 1 million animal and plant species, which undermines nature's contributions to people including the provision of food, feed, and clean water as well as climate regulation,[2,4,5] among others. In turn, many production systems ignore their reliance on functioning ecosystems to produce food and agricultural commodities and degrade the environment on which they depend.[2,6–8] As biodiversity and land use are tightly interlinked and interact in diverse ways,[8–10] it is essential to understand which and where regional opportunities and challenges exist to reconcile biodiversity conservation, food security, and sustainable land use.

Existing global syntheses reveal patterns of biodiversity and land use[7,10–13] yet entail thematic and spatial knowledge gaps. Among these, anthropogenic biomes, or anthromes, classify regions according to human population density, land use, and land cover including crops, pastures, and cities.[11] Anthromes were only retrospectively linked to biodiversity including vertebrate species richness.[12] Yet drivers of biodiversity change such as land-use change, fertilizer application intensity, food security, and governance remain largely neglected, implying crucial thematic knowledge gaps. More detailed biodiversity aspects such as ecosystem structure, species richness, and species traits were captured in analyzing patterns of anthropogenic drivers of biodiversity loss.[7] However, these findings lack spatially explicit insights and differentiated perspectives on land-use change and disregard food security. Moreover, anthropogenic threat complexes reveal patterns of human drivers of biodiversity change.[10] Although the patterns are valuable for testing hypotheses of biodiversity change, biodiversity outcomes were not included in their analysis. Furthermore, global trade of agricultural products can affect biodiversity across distant locations.[13,14] Such telecoupling effects pose ample conservation risks, but the impacts of global trade on biodiversity in distant locations remain underexplored.

The international community agreed to halt biodiversity loss and restore nature in a just and equitable way while enhancing human wellbeing calling for effective implementation of the Kunming-Montreal Global Biodiversity Framework (GBF),[15] its monitoring framework,[16] and the Sustainable Development Goals (SDGs).[17] A global stock-taking to assess current progress on the path to achieve the GBF targets is planned, and national biodiversity strategies and action plans are now being revised to translate global targets into national contexts. Although GBF targets are defined globally, GBF encourages the signatory countries to adapt the targets according to their national characteristics.[15] Neglecting regional specificity and existing knowledge on social-ecological patterns may result in untapped opportunities and misaligned interventions, undermining our capacity to achieve global policy targets. Therefore, insights into regional opportunities and challenges are urgently needed to tailor policies, i.e., prioritize policy targets in regions where they can effectively contribute to maintain and enhance biodiversity while ensuring human wellbeing.[18,19] Yet thematic and spatial knowledge gaps in earlier global syntheses limit possible regional considerations in policy tailoring. Synthesis research offers a way forward to integrate data and generalize knowledge in context-sensitive ways.[20,21] The use of these insights to inform policy has emerged as a priority in synthesis science.

Here, we provide a decision support tool for the international community to tap regional opportunities and identify challenges to effectively meet global biodiversity and sustainability targets. We identify human-nature archetypes, which we define as distinct social-ecological patterns that have emerged from and shape the interactions between ecosystems and humans.[21,22] Advancing the thematic and spatial detail of previous global syntheses, we focus on biodiversity intactness and threats, food security, agricultural land use, governance, remoteness, and human population density. We consider biodiversity as diversity of species and the land systems to which they belong.[4] Two research questions guided our empirical study. First, which human-nature archetypes occur across the globe and where? Second, which insights into regional opportunities and challenges do these archetypes offer to inform policy tailoring? To answer these questions, we integrated a set of social-ecological indicators with a consistent temporal reference, global coverage, and harmonized spatial resolution of 15 arcminute (0.25°) grid cells. To identify human-nature archetypes, we applied partitioning cluster analysis frequently used in sustainability science.[23] The resulting clusters of indicators constitute the human-nature archetypes that we interpret in terms of social-ecological interactions. We found a large gradient of archetypes ranging from best-maintained biodiversity in sparsely populated non-agricultural regions (31% of archetypes' land area; 2% of archetypes' population) to lowest biodiversity intactness in intensively farmed regions (4% of archetypes' land area; 48% of archetypes' population). Extending archetype application at science-policy interfaces,[24,25] we use the archetypes to tailor GBF targets and discuss the archetypes' role for enhancing policy effectiveness. Our findings highlight priority regions for policy actions on nature conservation, ecological restoration, and ecological intensification. This supports international and national decision makers to focus actions according to regional conditions in order to achieve global policy goals more effectively.

RESULTS

Human-nature archetypes provide a new unit of analysis

We identified 25 human-nature archetypes (Figures 1, 2, and S1) characterized by distinct combinations of social-ecological indicators reflecting interactive factors and processes. The indicators capture biodiversity intactness (estimated natural biodiversity that still remains intact despite human impacts[26]) and biodiversity threats, food security, agricultural land use,

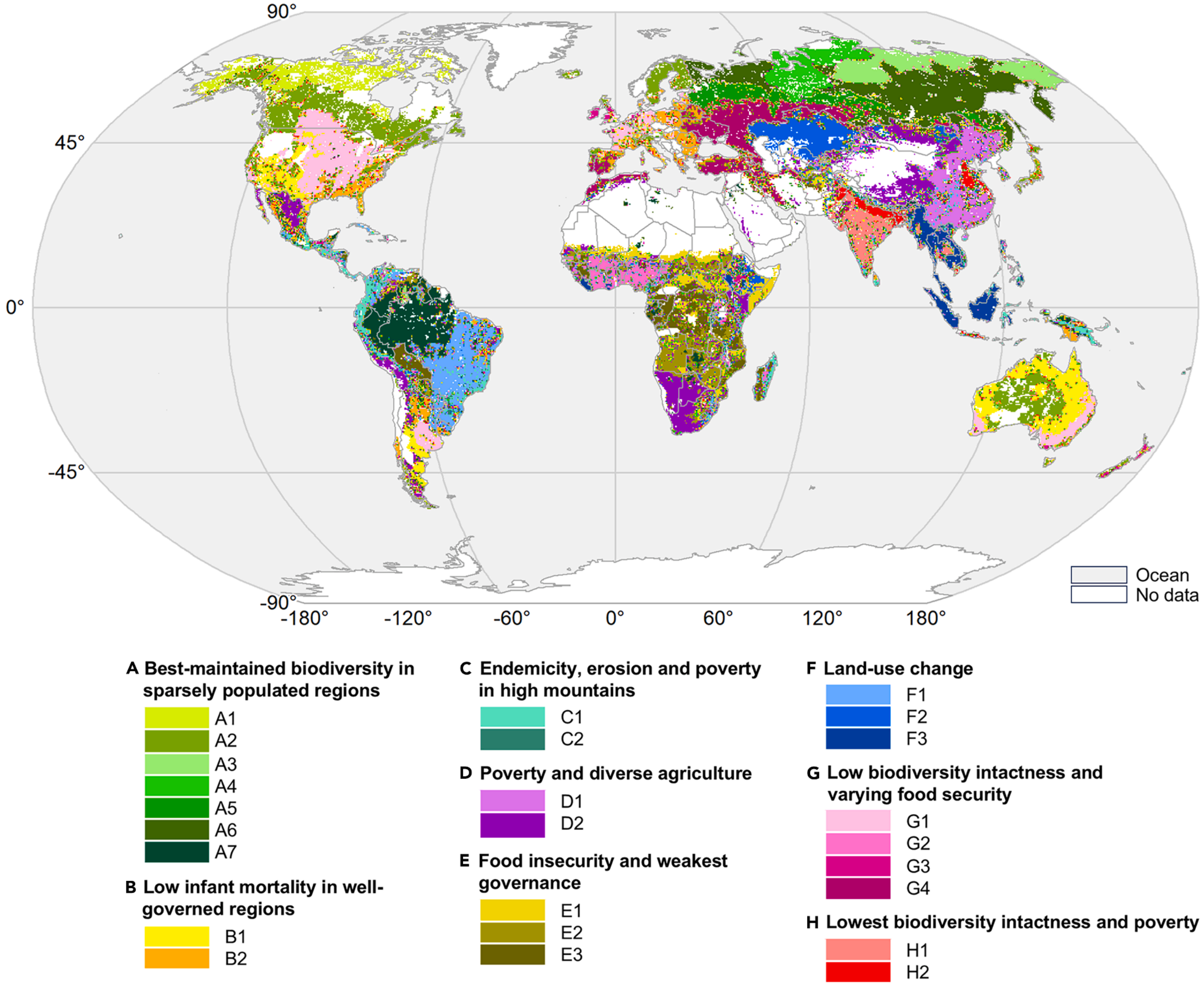

Figure 1. Human-nature archetypes depict eight broad groups of social-ecological patterns

Group A shows the best-maintained biodiversity in sparsely populated regions. Group B depicts areas with intermediate biodiversity intactness and low infant mortality in well-governed regions. Group C characterizes intermediate biodiversity intactness, endemicity, erosion and severe poverty in accessible high mountains. Group D combines intermediate biodiversity intactness, poverty and diverse agriculture. Group E shows intermediate biodiversity intactness, severe food insecurity and weakest governance. Group F denotes intermediate biodiversity intactness and land-use change. Group G represents low biodiversity intactness and varying food security in productive regions. Group H encompasses areas with the lowest biodiversity intactness, very high agro-potential and poverty. The country boundaries shown on the map do not imply the expression of any opinion whatsoever on the part of the authors concerning the legal status of any country, territory, city, or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

governance, remoteness, and human population density (for indicator details, see Table 2 and methods). We used the indicator combinations to characterize and label the archetypes (see synthesis in Figure 2). We categorized the archetypes into eight broad groups (groups A–H) (Figure 2) along a multi-dimensional gradient of decreasing biodiversity intactness, increasing threats to biodiversity (driven by land-use change, global trade, agriculture, and human settlements), increasing agricultural intensity, and decreasing governance quality.

On one side of the gradient, group A (Figure 2) depicts the best-maintained biodiversity covering 29.9 million km^2 (31% of archetypes' land area; Table 1). Being sparsely populated, these regions are home to about 110 million people (1.9% of archetypes' population) and many contain high shares of Indigenous Peoples' land (IPL) (13%–91%; Table 1). IPL depicts areas where IPL tenure is formally recognized and/or where Indigenous Peoples substantially determine land use to fulfill material and non-material needs.[27] Peoples are regarded as Indigenous when descending from populations who inhabited a region prior to conquest or colonization and who retain some, if not all, of their own socio-cultural, economic, and political institutions.[27,28] On the other side of the gradient, groups G and H (Figure 2) capture less and least intact biodiversity in 20% of archetypes' land area (Table 1). About 3.5 billion people (64% of archetypes'

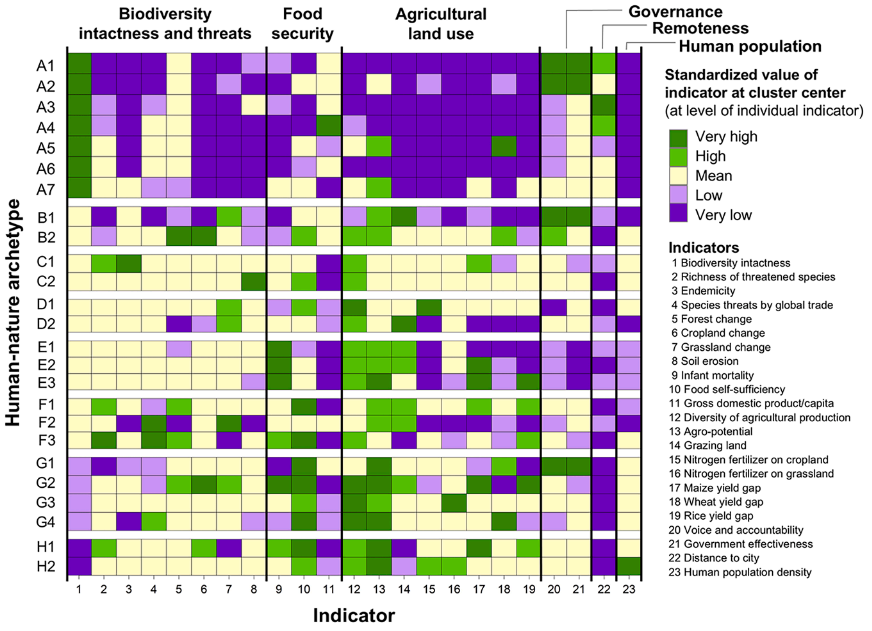

Figure 2. Distinct indicator combinations characterize the human-nature archetypes

Rows depict the archetypes, and columns show the indicators ordered in groups of social-ecological dimensions covering biodiversity intactness and threats, food security, agricultural land use, governance, remoteness, and human population density. To provide an overview, indicator values at cluster centers are standardized according to the minimum (extreme dark end of purple color) and maximum values (extreme dark end of green color) using equal intervals at the level of each individual z-scaled indicator. For further details see Table S1 and Figure S2.

population) live in these regions that encompass lower but often still substantial IPL shares (5%–52%; Table 1). Occupying only specific areas of the multi-dimensional gradient, the archetypes demonstrate the absence of regions with intact biodiversity despite high human impact. This highlights the widespread human influence on biodiversity and limited effectiveness of conservation efforts. We present an overview of the groups below, highlighting the most important dimensions of each group that show very low or very high values among all archetypes (Figure 2; for further details see Table S1 and Figure S2). A detailed description of the archetypes can be found in Table S1.

Group A: Best-maintained biodiversity

Group A depicts the best-maintained biodiversity in sparsely populated, non-agricultural regions (Figures 1, 2, and S2). These archetypes represent the best-preserved biodiversity among all archetypes. Actual values of the Biodiversity Intactness Index (BII, i.e., average species abundance relative to their abundance in intact ecosystems, see Table 2 and methods) reach 0.94–0.98, indicating that biodiversity is close to its natural potential. These archetypes differ largely in governance, species threats by global trade (of all commodities, weighted by biodiversity impact), income, and remoteness (Figure 2). For example, archetypes A1 and A2 depict very well-governed regions with very low species threats by global trade, intermediate income, and intermediate to high remoteness. In contrast, archetype A5 represents only moderate to weak governance combined with intermediate species threats by global trade, low income, and low remoteness, while A7 shows intermediate governance associated with low species threats by global trade, very low income, and intermediate remoteness. Overall, the archetypes in group A cover small area shares (2%–8%) and very small population shares (<1%) but intermediate to very large IPL shares, above all in most remote regions (13%–91%) (Table 1). They are found in tundra, boreal, temperate, subtropical, and tropical regions in central and northern Asia, northern America, the Amazon basin, central Australia, and northern Europe.

Group B: Low infant mortality in well-governed regions

In group B, intermediate biodiversity intactness across all archetypes (0.69–0.80 BII), indicating biodiversity significantly below its natural potential, is associated with very few to an intermediate number of species threatened by global trade, distinctive land-use change, low and very low infant mortality, and high agro-potential in moderately to very well-governed and accessible regions (Figures 1, 2, and S2). These archetypes represent small area shares (4%–5%) and very small and small population shares (0.1%–4%) and cover small to intermediate IPL shares (6%–34%) (Table 1). They occur in subtropical and temperate regions in Australia, northern and southern America, eastern Europe, and some parts of southern Europe.

Group C: Endemicity, erosion, and poverty in high mountains

Group C captures regions in which intermediate biodiversity intactness (0.64–0.79 BII) occurs together with either highest levels of endemicity or most severe soil erosion and severe poverty as well as moderate to weak governance in well- and very well-accessible high mountains (Figures 1, 2, and S2). Endemic species are prevalent in regions with a high richness of threatened species and moderate to weak governance (C1). Soil erosion is most severe in moderately governed, very well-accessible regions (C2). These archetypes encompass small area shares (2%), small population shares (3%–4%), and intermediate IPL shares (24%–26%) (Table 1). They are found in the northern and central Andes, central America, southern Brazil, Madagascar highlands, New Guinea highlands, and Ethiopian highlands.

Group D: Poverty and diverse agriculture

In group D, intermediate biodiversity intactness (0.64–0.79 BII) co-occurs with a pronounced contribution of grassland change to overall land-use change, low income, diverse and very diverse agriculture, and very weak to moderate governance (Figures 1, 2, and S2). Grassland change is associated with either very intensive fertilization of croplands (D1) or very large grazing land

Table 1. Complementary characteristics of human-nature archetypes

Human-nature archetype	Area (1,000 km^2)	Area (%)	Population (1,000 people)	Population (%)	Indigenous Peoples' land (1,000 km^2)	Share of Indigenous Peoples' land per archetype (%)
A1	2,635	2.7	51	0.0	347	13
A2	7,642	7.8	45,244	0.8	2,074	27
A3	2,510	2.6	172	0.0	2,288	91
A4	1,685	1.7	2,376	0.0	1,492	89
A5	3,133	3.2	37,479	0.7	410	13
A6	6,600	6.7	8,065	0.1	3,667	56
A7	5,700	5.8	16,395	0.3	2,033	36
B1	4,799	4.9	6,643	0.1	1,649	34
B2	4,018	4.1	234,119	4.3	247	6
C1	2,122	2.2	175,029	3.2	517	24
C2	1,443	1.5	205,176	3.8	371	26
D1	4,136	4.2	522,780	9.6	1,026	25
D2	6,650	6.8	71,156	1.3	2,170	33
E1	3,970	4.1	79,449	1.5	1,344	34
E2	4,650	4.8	131,130	2.4	909	20
E3	4,520	4.6	111,945	2.1	1,137	25
F1	5,785	5.9	129,924	2.4	417	7
F2	2,934	3.0	24,905	0.5	270	9
F3	2,819	2.9	159,519	2.9	1,553	55
G1	7,161	7.3	220,515	4.1	389	5
G2	2,550	2.6	237,935	4.4	1,320	52
G3	1,307	1.3	186,553	3.4	306	23
G4	4,926	5.0	236,292	4.4	311	6
H1	2,346	2.4	661,086	12.2	462	20
H2	1,779	1.8	1,925,321	35.5	81	5
Mean	3,913	4	217,170	4	1,072	29
Total	97,820	100	5,429,256	100	26,790	N/A

Characteristics accompany the indicator combinations presented in Figure 2. They include the archetypes' area (1,000 km^2 and %), human population (1,000 people and %), IPL (1,000 km^2), and share of IPL per archetype (%). IPL was calculated based on estimates provided by Garnett et al.[27] We acknowledge that these estimates included blank areas that do not necessarily indicate an absence of Indigenous Peoples or their lands, but rather areas for which an Indigenous connection could not be inferred based on publicly available geospatial data.

and very low cropland fertilization (D2). These archetypes cover low area shares (4%–7%), varying population shares (1%–10%), and intermediate IPL shares (25%–33%) (Table 1). They occur in arid, semi-arid, and humid temperate regions in southern and some parts of eastern Africa, the Himalayas, the Andes, the Mongolian Khangai Mountains, and eastern China.

Group E: Food insecurity and weakest governance

Group E shows intermediate biodiversity intactness (0.76–0.83 BII) in regions where people face severe food insecurity, crops are cultivated very extensively, and weakest governance prevails (Figures 1, 2, and S2). Very high infant mortality and very low income are associated with partly very high yield gaps. Weakest governance in these regions is indicated by a combination of low voice and accountability and very low government effectiveness. These archetypes represent low area shares (4%–5%), low population shares (2%), and average IPL shares (20%–34%) (Table 1). Respective regions include tropical forests and savannas across Africa and in the southern Amazon basin.

Group F: Land-use change

In group F, intermediate biodiversity intactness (0.75–0.76 BII) co-occurs with distinctive land-use change and partly very severe species threats by global trade in mainly sparsely populated, well- and very well-accessible regions (Figures 1, 2, and S2). In some regions, a large contribution of forest change to overall land-use change is associated with large and very large numbers of threatened species and very low income (F1 and F3). In other subsets, very severe species threats by global trade are combined with only moderate to weak governance (F2 and F3) and sometimes a very large contribution of grassland change to overall land-use change (F2). These archetypes are found in small area shares (3%–6%) where small population shares live (1%–3%) and IPL shares vary (7%–55%) (Table 1). They encompass mainly tropical and subtropical rainforests, dry forests, and

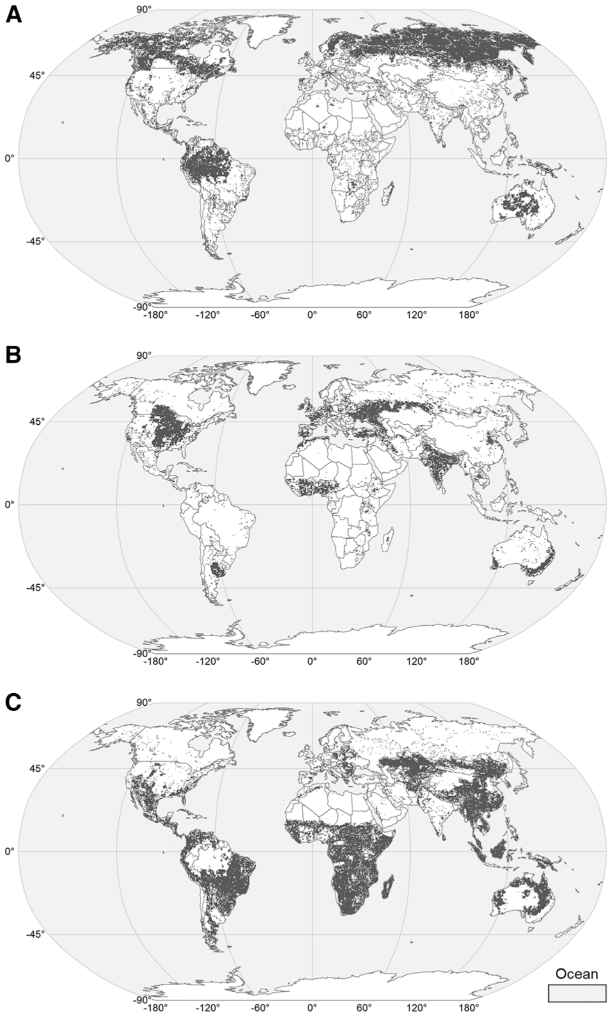

Figure 3. Human-nature archetypes highlight priority regions to tailor GBF targets

Priority regions for integrated spatial planning focused on (A) nature conservation (GBF Targets 1 and 3), (B) ecological restoration (GBF Targets 1 and 2), and (C) ecological intensification (GBF Targets 1 and 10). The country boundaries shown on the map do not imply the expression of any opinion whatsoever on the part of the authors concerning the legal status of any country, territory, city, or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

savannas as well as temperate and dry steppes in southeastern America, central Asia, and southeastern Asia.

Group G: Low biodiversity intactness and varying food security

Group G shows low biodiversity intactness (0.56–0.62 BII) in productive, very well-accessible regions where people generate moderate to very low income (Figures 1, 2, and S2). In some regions, only few species threatened by global trade are associated with very low infant mortality and very strong governance (G1). In other regions, pronounced contributions of forest, cropland, and grassland change to overall land-use change are linked with very high infant mortality, very low income, and only moderate to weak governance (G2), or large numbers of species threatened by global trade occur together with low infant mortality and low income (G4). Archetypes in this group represent very small and small area shares (1%–7%), small population shares (3%–4%), and varying IPL shares (5%–52%) (Table 1). They are found above all in temperate and tropical regions in northern America, Europe, southern Australia, western and northern Asia, and western Africa.

Group H: Lowest biodiversity intactness and poverty

Group H depicts the least intact biodiversity among all archetypes (0.28–0.32 BII) in very well-accessible regions with very high agro-potential, diverse agriculture, and high and very high food self-sufficiency (FSS) but with people living in poverty (Figures 1, 2, and S2). In these regions with a long history of agriculture, either a large contribution of cropland change to overall land-use change is combined with high richness of threatened species (H1), or very intensive agriculture indicated by high fertilizer inputs in cropland and grassland is combined with highest population density (H2). This group encompasses archetypes that represent small area shares (2%) but the largest population shares (12%–36%) and small to intermediate IPL shares (5%–20%) (Table 1). They are found mainly in southern and eastern Asia.

Archetypes are robust, and indicators vary in importance

Well-defined cluster properties (see Figure S2) and overall very high reproducibility (91% mean reproduction share of all grid cells' cluster membership, see Figure S3) demonstrate that human-nature archetypes are well differentiated and robust. According to the Fraiman Index,[29] the most important indicators at the level of the entire partition of archetypes include the distance to the nearest city (journey time in a given grid cell to reach the nearest city) and the area of grazing land (see low values of Fraiman Index depicting large differences in cluster results when omitting these indicators; Figure S4). In contrast, nitrogen fertilizer on cropland and species threats by global trade are among the least important indicators (see high values of Fraiman Index in Figure S4). Despite their low importance for the entire partition of archetypes, these indicators discern particular archetypes, e.g., highest nitrogen fertilizer application on cropland in archetype D1 and highest species threats by global trade in archetypes F2 and F3 (Figure 2). They enable the discussion of specific social-ecological patterns emerging only in some regions.

Archetypes reveal priority regions for policy actions

Human-nature archetypes provide insights that help tailor policies and support their spatial targeting so that they effectively foster the simultaneous enhancement of biodiversity, food security, and sustainable land use. The archetypes reveal distinct regions in which specific policy actions and spatial planning for nature conservation, ecological restoration, and ecological intensification are most effective. First, nature conservation would be an effective spatial planning focus (GBF Targets 1 and 3) in group A (Figure 3A) where biodiversity is best maintained, agriculture is not very relevant, and human population density is very low and in archetype C1 with the highest level of endemicity and high numbers of threatened species

(Figure 2). It helps protect remaining species and habitat diversity and exceptional concentrations of endemic species threatened by habitat loss and degradation. This concerns 33% of the archetypes' land area (Table 1). Second, ecological restoration of biodiversity, ecological integrity, and connectivity would be an effective focus of spatial planning (GBF Targets 1 and 2) in groups G and H (Figure 3B) with low and lowest biodiversity intactness, intensive and partly expanding agriculture, and limited food security. Restoration actions aim at recovering degraded ecosystems and associated ecosystem services such as nutrient cycling, pollination, and natural pest regulation upon which agriculture relies. These actions are relevant in 20% of the archetypes' land area (Table 1). Third, an ecological intensification focus in spatial planning (GBF Targets 1 and 10) would be essential in groups B–F (Figure 3C) with intermediate biodiversity intactness, partly high and very high yield gaps, and poverty limiting food security (Figure 2). Ecological intensification supports wild species that contribute to nutrient cycling, pollination, and pest regulation, which can enhance crop yields, fostering both biodiversity-friendly agriculture and food security. This concerns 49% of archetypes' land area (Table 1).

DISCUSSION

Human-nature archetypes advance sustainability debate

Current gaps in thematic and spatial knowledge on human-nature interactions limit possibilities to consider regional specificity in implementing global biodiversity and sustainability policy. Negligence of regional specificity may lead to unused opportunities and misaligned interventions, weakening chances to achieve policy targets. The human-nature archetypes provide refined insights into social-ecological patterns suited to tailor global policy. They present an integrated perspective capturing various dimensions of biodiversity intactness and threats, food security, agricultural land use, governance, remoteness, and human population density. The archetypes advance previous thematic and spatial insights gained from approaches that mapped how humans have altered the Earth using simplified indications of anthropogenic pressures, land use, and land cover.[10–12,30] For example, the human-nature archetypes differentiate three broad terrestrial conditions representing combinations of land-use drivers and anthropogenic pressures.[30] Group A mainly captures "large wild areas" dominated by natural ecosystems and small-scale land use.[30] These archetypes further differentiate the areas according to large variations in income, governance, and remoteness. Groups F–H largely correspond to areas indicated as "cities and farms."[30] Yet again, they demonstrate great differences in richness of threatened species, global trade impacts, land-use change, food self-sufficiency, governance, and human population density.

The human-nature archetypes advance the delineation of anthromes.[11] The anthromes result from a stepwise clustering approach using pre-defined thresholds to classify the terrestrial surface based only on population density, land use (croplands, pastures, and irrigated areas), and land cover (trees and bare lands). Using these variables, the anthromes capture the global extent and intensity of land-use footprints. Intersecting the anthromes with biodiversity data such as vertebrate species richness provided essential insights into spatial associations between land use and biodiversity change.[12] While the methodological and empirical simplicity yields important conceptual insights, the anthromes cannot provide spatially nuanced quantitative observations into social-ecological patterns necessary for targeted policy advice. In contrast, the human-nature archetypes integrate data on important biodiversity aspects (such as endemicity and species threatened by global trade), drivers of biodiversity change (such as land-use dynamics and fertilizer application intensity), food security, agricultural land use, and governance in the cluster analysis. Overall, the archetypes offer generic insights into the relationship between human activity and ecosystem integrity that can suitably underpin the tailoring of global policies, particularly in light of achieving GBF targets. The archetypes' focus on social-ecological patterns can be used to complement and contextualize findings derived from bottom-up approaches such as those framed as social-ecological production landscapes.[4] These provide valuable insights for outstanding land-use systems that depict harmonious interactions between people and nature. The growing number of case studies assessing social-ecological production landscapes capture important local indicators for which data are lacking at global scale, e.g., stakeholders' multiple value systems and decision making.[4] Yet locally specific indicators do not permit consistent comparison at global scale as the human-nature archetypes do.

The archetypes also refine typical human pressure complexes[10] with a focus on biodiversity, global trade impacts, land-use dynamics, food security, and governance. They reveal distinct regions with high numbers of threatened species in southeastern Asia (e.g., F3), very high endemicity in high-mountain regions (C1), and pronounced global trade impacts on species in central and southeastern Asia (F2 and F3). Moreover, variations in the contribution of forest and cropland change to overall land-use change differentiate pressure complexes in Europe and northern America (B1 and G1) and variations in governance those in the northern high latitudes (e.g., A1 and A6).

Refined insights into regional human-nature interactions can be drawn from these differentiations. To illustrate refinements, we present empirical evidence on interactions between constituting dimensions of archetypes reported in different continents. For example, "green revolution" legacies are evidenced for archetypes with least intact biodiversity, limited food security, and restricted governance (group H). In the respective regions, India promoted high-yielding crop varieties since the 1960s aimed at reducing yield gaps as a means to overcome hunger and poverty.[31] However, this agricultural intensification reinforced biodiversity loss, soil fertility decline, and soil pollution, among others, while poverty and food insecurity persisted.[32] Indigenous crop varieties (e.g., rice and millet in northern, central, and eastern India) were replaced, sometimes going extinct. This reduced agro-biodiversity and led to the loss of knowledge on Indigenous crop management.[31] Moreover, agricultural policies favored an excessive use of synthetic fertilizers and pesticides in many parts of India that contributed to soil degradation and pesticide residues in foods and the environment.[31,33] To build up vital human-nature interactions, restoration of degraded ecosystems, sustainable productivity gains, and the diversification of farming systems should be incentivized. Linking to global trade, food imports from "green revolution" legacy hotspots (e.g., into Europe) should implement legislation on deforestation-free products (EU Deforestation Regulation, http://data.europa.eu/eli/reg/2023/1115/oj) and the Corporate Sustainability Due Diligence Directive (CSDDD, http://data.europa.eu/eli/dir/2024/1760/oj). These legislations aim to reduce the European Union's impact on global deforestation decelerating biodiversity loss and improve environmental and human rights along supply and value chains.

Innovation bright spots are reported in regions where archetypes expose intermediate biodiversity intactness combined with severest food insecurity and weakest governance (E1). These bright spots depict situations in which social-ecological interactions were re-designed based on ecological principles to underpin agricultural production under environmental, demographic, and societal pressures.[34,35] For example, land conversion to agriculture driven by population growth, neoliberal market reforms, and structural adjustment policies contributed to biodiversity loss and soil exposure in southern Niger.[34,35] The resulting decline in agricultural productivity together with recurrent droughts aggravated the vulnerability and food insecurity of rural populations.[36] Farmer-managed natural regeneration (FMNR), an agroforestry-based practice,[34] reversed agriculturally driven biodiversity degradation and supported food security in these degraded regions. It entails the regrowth of trees and shrubs from remaining stumps and the soil seedstock using native biodiversity.[34,35,37] Essentially, the re-growing of trees and shrubs helps prevent soil erosion and re-enhances farmland biodiversity, ultimately fostering crop yields, food availability, and income generation.[34,37] In particular, leguminous tree species such as *Faidherbia albida* play a major role in FMNR in southern Niger as they fix nitrogen, thus decreasing nitrogen fertilizer demand, and are recognized by farmers to increase crop yields and to serve as an important source of fodder.[34] Low costs of replication and enhanced government effectiveness ensuring that communities have the mandate to manage the land and farmers benefit from their investments play a prominent role in FMNR implementation.[35] Integration of customary land-tenure systems within formal law and implementation of monitoring and enforcement systems are fundamental for FMNR success.[35] Having been implemented on more than 5 million hectares of agricultural land in Niger,[34] FMNR provides essential insights for innovative and positive scenarios of future development in a region that is surprisingly empty in the database of seeds of a good Anthropocene.[38]

Moreover, the border between archetypes in the eastern Amazon basin (A7) and the Cerrado in Brazil (F1) depicts a threat frontier. Along this frontier, native vegetation has been cleared for soybean cultivation and cattle pastures,[39,40] exploiting the high agro-potential in the Amazon basin (Figure 2). It is essential to prevent the progression of the threat frontier and maintain the remaining high biodiversity intactness in the eastern Amazon region (Figure 2) by slowing or halting deforestation, such as through agreements like the Soy Moratorium, a voluntary zero-deforestation agreement.[41] Expansion of the Soy Moratorium to the Cerrado (F1) can help avoid the conversion of remaining native vegetation for crop production in already intensively used regions.[42] Enhancing poorly defined with conservation-oriented land-tenure schemes is essential to reduce deforestation.[40] The large overlap of intact forests and IPL in the agricultural frontier region between the eastern Amazon basin and the Cerrado highlights the importance of recognizing IPL tenure to maintain natural habitats.

Archetypes support tailoring of policy targets

GBF presents a window of opportunity to globally reconcile biodiversity enhancement, food security, and sustainable land use overcoming the persistent division between the Global Biodiversity Plan 2011–2020[43] and the SDGs.[17] The human-nature archetypes deliver important insights for tailoring GBF targets to regional conditions. Thereby, the current level of biodiversity intactness, food security, and intensity of land use indicates which type of reconciliation actions is effective.[18] We discuss where specific policy actions can best maintain and enhance biodiversity while ensuring that people can meet their food and livelihood needs, considering governance a key enabler of transformative change.

In group A and archetype C1, prioritizing integrated spatial planning for nature conservation (GBF Targets 1 and 3) can best protect species and habitat diversity where they still exist and an exceptionally high richness of endemic species under threat. Respective countries can suitably contribute to achieve the global conservation target by focusing their national spatial planning on effective conservation and management of wild species and natural habitats, including areas of high biodiversity importance and ecosystems of high ecological integrity. A key opportunity would be to widen the network of protected areas and other effective area-based conservation measures above the globally defined 30% area target (GBF Target 3). This reflects the globally uneven distribution of intact biodiversity and endemic species, reinforcing the potential of nationally adjusted area targets for nature conservation.[44] In these efforts, revitalization and strengthening of Indigenous-led conservation is essential to increase the spatial extent of effective and just conservation.

However, archetypes A3–A7 and C1 depict only weak to intermediate governance, clearly challenging conservation planning and implementation (Figure 2). Challenges include a lack of well-defined land tenure rights, limited compliance and enforcement of conservation regulations, and ineffective regulatory measures.[40–42] These insights on important conservation challenges contrast an earlier global study that calculated low challenges for most of these regions only based on conservation area and gross domestic product (GDP).[44] The greater challenges indicated by the human-nature archetypes highlight the need for actors beyond national governments including provincial governments, Indigenous and local communities, and the private sector to urgently be recognized and integrated in tackling biodiversity challenges. In particular, polycentric governance[45] can foster the required institutional fit while recognizing Indigenous and traditional territories (GBF Targets 1 and 3) prevalent in archetypes A3–A7 and C1 (see Table 1).

In groups G and H, giving priority to integrated spatial planning that emphasizes ecological restoration (GBF Targets 1 and 2) can effectively contribute to recover the strongly degraded biodiversity intactness in intensively used agricultural systems. This underpins the urgent need of re-establishing healthy interactions between biodiversity and food production. In these regions with severely exhausted natural habitats and species pools, a re-design of agricultural systems according to the principles of ecological restoration would enable ecosystem services and ecological integrity to recover. This is an essential precondition to support regional food security and national sovereignty over land and food instead of compensating food production elsewhere. If respective countries would adjust the globally defined target and plan to restore >30% of their degraded areas at national level, then chances of reaching the global restoration target would greatly increase.

Ecological restoration depends on active participation of local people, underlines the importance of Indigenous land management, and supports Indigenous Peoples' cultures and languages as living libraries of traditional ecological knowledge in the respective regions.[46] However, capacities to effectively design and implement restoration actions[47] are limited in many regions with restoration priority (groups G and H), indicated by weak to moderate governance (Figure 2). Major challenges encompass the limited awareness of biodiversity, limited integration of traditional and Indigenous knowledge in policy, and incoherence between sectoral policies in implementing sustainable development targets.[4,33] Collaborative efforts at national and global scales would be essential to build up these capacities considering partly high and very high infant mortality as well as low and very low income (Figure 2).

In groups B–F, an integrated spatial planning focus on ecological intensification (GBF Targets 1 and 10) can effectively help overcome biodiversity degradation co-occurring with food security limitations and unsustainable agriculture. Ecological intensification draws attention to the management of wild species that provide regulating and supporting ecosystem services (e.g., nutrient cycling, pollination, and pest regulation).[48,49] Re-establishing wildlife habitats surrounding or embedded in agricultural landscapes can provide foraging, nesting, and refuge space for service-providing species, which in turn can support and stabilize crop yields. As an innovative approach, agroecology (GBF Target 10) supports ecological intensification by highlighting the role of biodiversity to foster synergies, efficiency, and resilience, essentially implying a re-design of agricultural and food systems.[50,51] Resting on responsible governance, social values, and knowledge co-creation, it turns away from the paradigm of maximizing productivity toward optimizing the effectiveness of biodiversity while maintaining productivity and ensuring affordable and healthy diets. Hence, in groups B–F, agroecology provides a promising framework to sustainably transform land and food systems,[18] an urgently acknowledged requirement to solve the biodiversity crisis.[6,52,53] In archetype C1, it should be accompanied by conservation measures to provide special protection for the endemic species prevailing there, as outlined above.

In regions with ecological intensification priority, planning and implementation capacities are likely greater in Australia, Europe, and northern America, given better governance (group B, Figure 2). However, cropland expansion and intensive agricultural production challenge efforts in some of these regions (e.g., in eastern Europe and southeastern United States of America). In contrast, planning and implementation capacities for ecological intensification are clearly limited in regions that suffer from weak and very weak governance, above all in Africa (group E, Figure 2). Challenges arise from limited dialogue between relevant departments involved in natural resource management, inefficient formal institutions, government agents' limited interest in capacity building, and insecure and short-term land tenure disincentivizing investments in land,[34,37] among others. These insights extend an earlier study that also calculated intermediate to high challenges for implementing nature conservation areas in some of these regions.[44] Yet innovation bright spots demonstrate the clear potential of a locally managed re-design of agricultural and food systems supported by effective governance at national level (see previous subsection), efforts toward which the international community can well contribute.

Archetypes help enhance policy effectiveness

The archetypes depict recurrent patterns, meaning typical combinations of social-ecological factors and processes, which support integrative evaluations of human-nature interactions. The archetypes do not encompass all possible configurations but only a manageable number of patterns that occur repeatedly. They provide knowledge in between regional and global scales that advances generalization and comparison at an intermediate level. The spatial indication of human-nature archetypes enables international and national decision makers to compare regions and assess their similarities and differences in a broader perspective.

The archetypes present a framework for more effectively planning and implementing policy actions. Specific policy targets and associated actions can be tailored to those conditions where they can most effectively contribute to achieve global sustainability. This offers decision support for the international community to evaluate regional opportunities and challenges for meeting global policy targets. The human-nature archetypes also offer the opportunity for a consistent global stock-take of current conditions serving as a baseline for future inventories and trend analyses if the datasets used here are continuously collected. Furthermore, our methodological approach can accommodate data with higher spatial, thematic, or temporal details, which permits more nuanced insights into spatial social-ecological patterns to be explored in future studies.

Moreover, human-nature archetypes support the discussion of scaling domains depicting regions with similar social-ecological conditions where reconciliation strategies can be tested. Assuming that suitable strategies are comparable under similar conditions,[36] the archetypes support the scaling of strategies and foster learning across regions. For example, agroforestry, a strategy that helped re-enhance ecological processes and food security in southern Niger, can also be assumed effective for re-establishing healthy social-ecological interactions in other parts of the Sahel zone located in the same archetype (E1). When scaling strategies, they need to be adjusted to the environmental, governmental, and socio-cultural conditions in the new regions (such as using native tree species, traditional knowledge, and suitable organizational structures).

Uncertainty in archetype analysis

As all global data syntheses, the archetypes generalize real-world complexity. They refine existing syntheses with a view on diverse features of biodiversity, food security, agricultural land use, and governance, allowing a more nuanced interpretation of social-ecological interactions. The unsupervised clustering approach used in this study avoids uncertainties associated with expert-defined thresholds used in earlier syntheses.[11,54] In these syntheses, pre-defined classification thresholds served as cutoff points to categorize observations in specific groups. However, their definition relies on subjective decisions. For example, there is general evidence that agricultural expansion decreases biodiversity. Yet there is no agreement on the maximum cultivated area in agricultural landscapes that still ensures functional natural habitats and the provision of nature's contributions to people.[55] This depends on the landscape context (e.g., characterized by field margins and natural vegetation remnants) and conservation targets.[56]

As a cluster-specific procedure, we used stability considerations to select the optimal number of clusters and evaluate their reproducibility addressing internal validity.[57] The clusters are very well reproducible (see Figure S3) and their properties well defined (see Figure S2). For example, in an archetype found in the Amazon basin (A7), most indicators vary very little. This is shown by the very small size of boxplots (see Figure S2), meaning a very small range of indicator values within the middle 50% of grid cells categorized in this archetype. These indicators encompass BII, land-use change, infant mortality, income, and governance. In other indicators, some variation is found such as in the richness of threatened species and diversity of agricultural production, while FSS varies to a greater extent. In the multi-dimensional perspective of archetypes, however, these variations did not result in distinct patterns.

We used globally available data with sub-national resolution to indicate social-ecological dimensions aiming to integrate data with consistent underpinnings. For example, land-use information from the History Database of the Global Environment (HYDE) served as source data for BII, grazing land, and nitrogen fertilizer application on cropland and grassland. Moreover, data on harvested area, crop yields, and land suitability from the Global Agro-Ecological Zones (GAEZ) database were used to generate FSS, agro-potential, and yield gap data. However, the reliability of land-use estimates is limited for some countries (e.g., China) entailing regional uncertainties. Data processing implies further sources of uncertainty. For example, misclassification in remote sensing products related to annual classification errors can accumulate, particularly affecting the precision of long-term datasets (e.g., land-use change). Overall, the source data and their processing entail a varying degree of uncertainty for our analysis. Our estimation of cluster sensitivity to the omission of indicators (see Fraiman Index in Figure S4) shows the indicators' importance, which enables a discussion of how influential their uncertainty is for the partition of archetypes.

The input data used in our study are differently resolved in space, implying scale-related uncertainties. To balance the base resolution of input data and ensure their comparability and compatibility, we conducted our analysis at 15 arcminute (0.25°) resolution. This aims at preserving a suitable level of detail for more finely resolved data (e.g., distance to city) while not suggesting a false level of detail for coarsely resolved data (e.g., governance). Advancing earlier global syntheses, we included sub-nationally resolved gross domestic product (GDP) data as an income indicator. This enables a more detailed perspective on regional income distribution. Moreover, choosing a 15 arcminute grid cell resolution for our analysis rather than administrative units reveals heterogeneity within these units. Values for originally lower resolved input data (e.g., national governance data) were homogenously assigned to all grid cells in that spatial unit (e.g., country). Combination with higher resolved data can provide some more details for interpretation. For example, the distance to the nearest city differentiates the broad governance data. We assume that in less accessible regions, governments can less effectively implement policies and provide quality public and civil services, and citizens may be restricted in participating in elections and political processes. Moreover, the varying temporal coverage of input data also influences uncertainty. To mediate these effects, we focused on temporally consistent datasets. The baseline centers around the year 2015 (i.e., data available for 2015 or the closest year to 2015), as adequate data for more recent years were not available for many dimensions. Hence, more recent processes (e.g., re-intensified deforestation in the Amazon or GDP changes in Europe) remain beyond the scope of our study.

Our human-nature archetypes are constrained by the lack of high-resolution data. For example, the diversity of land-use actors, including farmer organizations, investors, distant landowners, and value chain actors, remains systematically absent in global data. In particular, the actors' motivations, decision making, and embeddedness in potentially far-reaching networks are inherently difficult to capture in a spatially explicit way. Globally consistent data are equally absent for land governance, land-use policies, and social outcomes of biodiversity conservation. Currently, the archetypes focus on terrestrial ecosystems. This focus can further be broadened once global information about the impacts of human water uses (including blue water and groundwater use) on the functioning of aquatic ecosystems becomes available. Ongoing shifts from focusing on either natural or social science perspectives toward explicit social-ecological approaches that lead to enhanced data availability can support future efforts to refine the current generalization.

Conclusion

The human-nature archetypes systematically integrate ecosystem integrity and requirements with human activity and needs, bridging disciplinary and sectoral divides. They redirect the global debate toward seizing social-ecological benefits on all land areas to improve system efficiency and policy effectiveness, reflecting the uneven distribution of biodiversity intactness and threats, food security, and land-use activities. The archetypes help clarify where global policy targets such as those framed in the GBF provide incentives to sustainably transform land and food systems, which enables policymakers to assess a region's opportunities and challenges. For example, integrated spatial planning emphasizing nature conservation (GBF Targets 1 and 3) would be most beneficial in archetypes with high biodiversity intactness and pronounced concentrations of endemic species to safeguard remaining vital ecosystems. In contrast, integrated spatial planning focused on ecological restoration (GBF Targets 1 and 2) would be most effective in archetypes with low and lowest biodiversity intactness and intensive agriculture to reverse ecosystem degradation and food insecurity. Global priorities can now be set allowing the GBF Fund Council, established to support GBF implementation, and other funding agencies to focus their efforts in approving implementation projects.

Yet how does the world look like when GBF targets will be reached in the future? For example, can the archetypes that currently depict poverty together with diverse agriculture or severe food insecurity combined with weakest governance evolve in such a way that they resemble those currently portraying best-maintained biodiversity? Development trajectories have differed in the past and will do so in the future, making simple convergence between archetypes practically impossible. To steer transformative change for sustainable future development, some archetypes would require improvements in social dimensions (e.g., governance) to reduce the increasing pressure on ecosystems and to stabilize ecological conditions (e.g., biodiversity intactness). In other archetypes, restoration of biodiversity and associated ecosystem services (e.g., nutrient cycling) would be a prerequisite to improve social dimensions (e.g., food availability and poverty reduction), or both social and ecological advances would be necessary. Future research could explore the different option spaces reflecting current conditions and reveal specific potentials and conflicts lying ahead.

Clearly, the prevalent and partly high share of IPL across the human-nature archetypes highlights that there is no way to achieve global biodiversity and sustainability goals without Indigenous Peoples. They have managed social-ecological systems for centuries in all archetypes. This reinforces the plea for taking up evidence-based contributions that Indigenous Peoples have delivered to the global discussion about biodiversity conservation, sustainable land management, and food security. They offer important lessons for strengthening the resilience of land and food systems that should be comprehensively considered in future research and decision making.

Over 200 years ago, Humboldt assumed that “everything is interconnected” and if the individual parts of a system and their interactions are known and integrated in a system’s perspective, then understanding and steering of the system should be possible. Systematic observation of interlinked vegetation, abiotic environmental conditions, and land use led Humboldt to strategically locate and ensure consistency in scientific measurements and generalization of results. The human-nature archetypes deliver useful insights to inform the international community on relevant monitoring indicators to track progress in achieving the GBF targets. These indicators can help to monitor interactive trends in ecosystem conservation and restoration, food security and land use.

METHODS

Social-ecological indicators

To characterize human-nature archetypes, we quantitatively indicated social-ecological dimensions whose interdependencies were emphasized as important for achieving global sustainability priorities.[2,58] We chose indicators along six dimensions representing critical drivers and outcomes of biodiversity-food-agriculture interactions including biodiversity intactness and threats, food security, agricultural land use, governance, remoteness, and human population density[2,7,10] (Table 2). Our study demands quantitative data available with global coverage and high spatio-temporal resolution. Data need to be finely resolved in space to support recognition of fine-scale patterns as a prerequisite for developing targeted strategies to effectively achieve sustainability goals. This requires a sub-national resolution. To warrant comparability and compatibility, data would ideally reflect the same spatial resolution and temporal collection intervals and be derived using consistent methodologies. Using these criteria, we screened available, sub-nationally resolved global data initially identifying 29 suitable indicators. Some of these indicators were generated using similar source data and were hence not fully independent of each other. To avoid collinearity and select indicators that are important for the overall data variance, we assessed Spearman correlations and the variance distribution. This resulted in a final set of 23 indicators used to identify human-nature archetypes. Their temporal reference centers around the year 2015 because most data were available for 2015 or a year close to it (Table 2; for further details see Tables S2 and S3). Details on the indicators are given below.

Biodiversity intactness and threats

To represent biodiversity intactness and threats, we selected indicators that specify how much of a region’s natural biodiversity is left intact, threatened by extinction, or susceptible to habitat loss as well as global trade and land-use change as drivers of biodiversity loss and soil erosion. This selection included eight integrative indicators encompassing the Biodiversity Intactness Index, richness of threatened species, endemicity, species threats by global trade, forest change, cropland change, grassland change, and human-induced soil erosion (Table 2). In the absence of a globally consistent biodiversity monitoring, we used the BII,[26,79–81] which provides an estimate of the average abundance of a broad range of species in a given area in relation to their abundance in intact reference ecosystems.[79] As it is based on an unprecedented large number of field studies and observations across the globe and represents all major biomes and land uses, the BII enables coherent global comparison. We further characterized the intactness of biodiversity using the richness of threatened species (RTS).[59] RTS helps to gain differentiated insights into regions where species may be more affected by human activities. Land use, land-cover change, and growing human populations often threaten species and may drive their extinction[82,83] and can be more influential than environmental factors (e.g., insularity and temperature).[84] Moreover, we used endemicity (END) data, i.e., restriction to a geographical area,[5,60–63] to indicate species’ susceptibility to the effects of habitat change/loss and extinction caused by human activities. In addition, we captured species threats by global trade (TGT).[64] The production and consumption of goods and services can impact species locally but also elsewhere. Applying the biodiversity footprint method,[85] Moran and Kanemoto[64] attributed anthropogenic species threats to one or more causal economic sectors including agriculture, forestry, transport, residential and commercial development, and others. TGT data represent species threats associated with the consumption in the United States of America, Europe, China, and Japan. We summed the worldwide species threats linked to consumption in all these countries, thus capturing the total impacts of major players in world trade. The reason for using a biodiversity footprint approach is that people living in one archetype could be

Table 2. Social-ecological indicators used for analyzing human-nature archetypes

Social-ecological dimension	Abbreviation	Indicator (unit)	Time reference (year)	Spatial resolution	Source references
Biodiversity intactness and threats					
(1) Biodiversity intactness	BII	Average species abundance relative to their abundance in intact ecosystems (unitless)	2015	5′ grid cells	Hill et al.[26]
(2) Richness of threatened species	RTS	Richness of threatened species of mammals, birds, and amphibians (total number of all species)	2015	10 × 10 km grid cells	Pimm et al.[59]
(3) Endemicity	END	Range-rarity of all terrestrial species (summed area share)	2015	0.5° grid cells	International Union for Conservation of Nature,[5] BirdLife International,[60] Collen et al.,[61] Selig et al.,[62] Kreft and Jetz[63]
(4) Species threats by global trade	TGT	Species threats caused by key global trade players (species equivalents)	1990–2015	Polygons	Moran and Kanemoto[64]
(5) Forest change	FCH	Relative contribution of forest change to gross land change rates, accounting for area gains and losses per grid cell (% change per year)	2000–2040	0.5° grid cells	Fuchs et al.[65]
(6) Cropland change	CCH	Relative contribution of cropland change to gross land change rates, accounting for area gains and losses per grid cell (% change per year)	2000–2040	0.5° grid cells	Fuchs et al.[65]
(7) Grassland change	GCH	Relative contribution of grassland change to gross land change rates, accounting for area gains and losses per grid cell (% change per year)	2000–2040	0.5° grid cells	Fuchs et al.[65]
(8) Soil erosion	ERO	Water erosion of soil (t/ha·year)	2012	250 × 250 m grid cells	Borrelli et al.[66]
Food security					
(9) Infant mortality	IMR	Infant mortality rate (number of children who die before their first birthday per 1,000 live births)	2015	0.5′ grid cells	Center for International Earth Science Information Network[67]
(10) Food self-sufficiency	FSS	Ratio of calorie production/consumption (unitless)	2010	5′ grid cells	Pradhan et al.[68,69]
(11) Gross domestic product/capita	GDP	Gross domestic product/capita (US$/capita)	2015	Highest sub-national administrative division	Kummu et al.[70]

(*Continued on next page*)

Table 2. ***Continued***

Social-ecological dimension	Abbreviation	Indicator (unit)	Time reference (year)	Spatial resolution	Source references
Agricultural land use					
(12) Diversity of agricultural production	DIVA	Shannon diversity index of food production (unitless)	2005	5′ grid cells	Herrero et al.[71]
(13) Agro-potential	AP	Maximum suitability index across all crops/pasture and input levels (unitless)	Baseline 1981–2010 climatology	5′ grid cells	Food and Agriculture Organization of the United Nations, and International Institute for Applied Systems Analysis[72]
(14) Grazing land	GRAZ	Total land used for grazing (km^2)	2015	5′ grid cells	Klein Goldewijk et al.[73]
(15) Nitrogen fertilizer on cropland	NCRO	Annual synthetic nitrogen fertilizer used in cropland ($t\ N/km^2 \cdot year$)	2013	0.5° grid cells	Lu and Tian[74]
(16) Nitrogen fertilizer on grassland	NGRA	Sum of manure nitrogen deposition, manure application, and synthetic fertilizer nitrogen input to pastures and rangelands ($t\ N/km^2 \cdot year$)	2015	0.5° grid cells	Xu et al.[75]
(17) Maize yield gap	MYG	Relative yield gap between potential attainable and actual yield (% potential attainable yield)	2010	5′ grid cells	Food and Agriculture Organization of the United Nations, and International Institute for Applied Systems Analysis[72]
(18) Wheat yield gap	WYG	Relative yield gap between potential attainable and actual yield (% potential attainable yield)	2010	5′ grid cells	Food and Agriculture Organization of the United Nations, and International Institute for Applied Systems Analysis[72]
(19) Rice yield gap	RYG	Relative yield gap between potential attainable and actual yield (% potential attainable yield)	2010	5′ grid cells	Food and Agriculture Organization of the United Nations, and International Institute for Applied Systems Analysis[72]
Governance					
(20) Voice and accountability	VA	Perceptions of citizens' ability to participate in elections, freedom of expression, freedom of association, and free media (unitless)	2015	National	World Bank[76]

(*Continued on next page*)

Table 2. *Continued*

Social-ecological dimension	Abbreviation	Indicator (unit)	Time reference (year)	Spatial resolution	Source references
(21) Government effectiveness	GOE	Perceptions of public and civil service quality, independence from political pressures, quality of policy formulation and implementation, and credibility of government's commitment to policies (unitless)	2015	National	World Bank[76]
Remoteness					
(22) Distance to city	DIST	Travel time to nearest city (minutes)	2015	1 × 1 km grid cells	Weiss et al.[77]
Human population					
(23) Human population density	POP	Number of people living in a region (number of persons/km^2)	2015	0.5′ grid cells	Center for International Earth Science Information Network[78]

For further details and descriptive statistics of indicators, see Tables S2 and S3.

consuming very few resources from within that region but importing large amounts of resources from other regions. By capturing the total use as opposed to merely local use of resources, we more accurately characterize the resource use in each archetype. The data cover a large share and diversity of the world's trade players but not all of them, restricting insights to major global trade players. Moreover, we indicated land-use change as another anthropogenic biodiversity threat.[7] We used data on the relative contribution of forest change (FCH), cropland change (CCH), and grassland change (GCH) to overall rates of land-use change.[65] These data enable an exploration of biodiversity modifications including habitat change and variations in associated ecosystem services, e.g., provision of food and resilience.[55,86–88] The data on land-use change capture observational data and a reference scenario of future land-use change.[65] Furthermore, we indicated human-induced soil erosion (ERO) caused by water erosion.[66] This allows to explore risks of aggravated soil erosion mainly driven by changing land use and land management as well as implications for land productivity.

Food security

Food security was represented by three indicators reflecting food availability and access.[89] In the absence of global data on undernourishment or stunting, we used infant mortality rate (IMR) to indicate food security. IMR is found to be negatively correlated with food supply (addressing food availability) in lower-income countries and with food access across countries with varying income levels.[90,91] We indicated IMR by the number of infant deaths for every 1,000 live births.[67] Moreover, considering that food security depends on environmental, managerial, and economic factors, we captured food self-sufficiency and peoples' ability to purchase food. We used data on a region's food self-sufficiency (FSS) reflecting the proportion of total calorie production and consumption.[68,69] We considered a region as food self-sufficient when the total regional calorie production was sufficient to meet its consumption. Moreover, we represented income using sub-national per capita GDP[70] as spatially well-resolved income data are unavailable at global scale. This served to indicate people's ability to purchase sufficient calories for sustaining an active and healthy life. This indicator pertains to the affordability of food as an important determinant of food security.[89] Interpreting income together with food self-sufficiency enables a more detailed discussion of food security. For example, we assume that people living in a region with lower food self-sufficiency but higher income may meet their food demand through additional purchase, though relying more on (global) trade. GDP is only a rough proxy for access to food. More fine-grained metrics of hunger, food poverty, and access to healthy diets are available in some regions but lacking at global scale.

Agricultural land use

Agriculture is a multi-dimensional land-use activity, which we characterized by focusing on the diversity, extent, and intensity of agricultural production as well as opportunities to increase agricultural productivity. This sets the basis to discuss interlinkages between agricultural land use, biodiversity, and food security. We used eight indicators capturing the diversity of agricultural production, agro-potential, area of grazing land,

and nitrogen fertilizer input in cropland and grassland, as well as yield gaps for maize, wheat, and rice. We covered the diversity of agricultural production (DIVA) to explore associations of agricultural diversity with food security. DIVA can stabilize and increase food availability and access depending on the environmental and socio-economic context, hence providing an important strategy to improve food security. We indicated DIVA by the number of crops grown and livestock raised in a grid cell and their distribution in this grid cell.[71] Moreover, agro-potential served to identify production opportunities and attractiveness of expanding agricultural land use into land suitable for agricultural production. We indicated agro-potential (AP) by land suitability for agricultural production provided by the GAEZ database.[72] It considers eco-physiological characteristics and climatic and edaphic requirements of crops. We used the maximum suitability index across all crops/pasture and input levels. Managing agro-ecological opportunities and limitations and recognizing the most suitable crop options support effective land-use planning. Furthermore, we captured the extent and intensity of agricultural production to discuss outcomes of agricultural land use for biodiversity and food security. In terms of area extent, we selected data on the area of grazing as one of the most widespread forms of land use worldwide[92] and one of the main drivers of biodiversity loss. We used the area of grazing land (GRAZ), the total land used for grazing in the HYDE 3.2 database.[73] In addition, we indicated synthetic nitrogen fertilizer application as it markedly increases food production, but often at the expense of biodiversity. In turn, the absence of synthetic fertilizer application offers the opportunity that diversification synergistically stabilizes and improves both biodiversity and yields.[93] Better managing these relations remains a major challenge for policy makers. We used the annual synthetic nitrogen fertilizer input in cropland (NCRO) matched with HYDE 3.2 land-use maps.[74] To cover grassland fertilization (NGRA), we used the sum of annual manure nitrogen deposition, manure application, and synthetic nitrogen fertilizer input on pastures and rangelands.[75] Both nitrogen fertilizer datasets provide critical driver information to discuss the intensity of agricultural land use and biodiversity feedback patterns. Moreover, yield gaps provide insights into potentials to increase food production in the future as a cornerstone of food security. Capturing major staple food crops, we indicated yield gaps for maize, wheat, and rice (MYG, WYG, and RYG) within their growing regions, expressed as the percentage of potential attainable yield.[72]

Governance, remoteness, and human population density

Finally, we captured governance, remoteness, and human population density, as they play important roles in reconciling interconnected concerns of biodiversity, food security, and sustainable land use. Governance encompasses processes of decision making, rule setting, and decision enforcement, whose effectiveness determines chances to conserve biodiversity and use land sustainably while ensuring food security. We indicated governance by the national average of aggregated indicators reflecting perceptions of the public and private sector, non-governmental organizations, enterprises, and citizens.[94] We used the dimension of voice and accountability (VA) to capture processes by which governments are selected, monitored, and replaced.[76] We also included government effectiveness (GOE) to capture a government's capacity to effectively formulate and implement policies.[76] Furthermore, remoteness from markets and decision making provides insights into access to goods and services that affect biodiversity, food security, and land use. We indicated remoteness by the distance to the nearest city (DIST), meaning the journey time in a given grid cell to reach the nearest city.[77] Finally, human population density (POP) expresses food and other demands to be satisfied, pressurizing land resources and the number of people affected by biodiversity degradation and food insecurity. We indicated human population density by the number of people per km^2 living in a region.[78]

Cluster analysis

We identified the human-nature archetypes using cluster analysis commonly applied for unsupervised pattern recognition.[23] Clustering serves to reveal groups in data based on their similarities and differences, providing insights into the structure of the multi-dimensional data space spanned by the selected indicators. It categorizes data into groups or clusters with similar characteristics depicting recurrent patterns. The patterns are represented by the indicator combinations at the cluster centers. These combinations portrayed the archetypes and provided the basis to discuss factors and processes that typically result from and shape the interactions between biodiversity, food security, agricultural land use, governance, remoteness, and human population density.

In preparing the cluster analysis, we used the initial set of 29 indicators and re-sampled them all to an intermediate 15 arcminute spatial resolution (grid cells) to harmonize differences in indicator resolution. Moreover, we normalized all indicators using their mean and standard deviation (z-scaling) to enable consistent mean-centering and unit scale differences as a basis for comparison. We investigated correlations between these z-scaled indicators and performed a principal component analysis.[95] To ensure the use of largely uncorrelated indicators that hold most of the structure information, we selected those indicators that had a Spearman correlation coefficient $\rho \leq |0.75|$ and/or an absolute loading $\geq |0.55|$ in the first 15 principal components, explaining 88% of the total variance. This yielded the 23 indicators described above (Table 2) covering 172,841 grid cells (69% of global land area and 77% of ice-free land area) that we used to identify the archetypes. The remaining six indicators were highly correlated with other indicators, contributed very little to the data variance, and were therefore excluded from the cluster analysis. These encompassed human appropriation of net primary productivity (HANPP),[96] cropland area,[73] harvested area,[72] Human Development Index (HDI),[70] share of agriculture, forestry, and fishing of national GDP,[97] and control of corruption.[76] Moreover, we adjusted datasets with few extreme values that skewed the overall data distribution in order to adequately focus on the majority of grid cells. To handle such skewed data, we winsorized the datasets, i.e., replaced the extreme observations ($\leq 0.5^{th}$ or $\geq 99.5^{th}$ percentile) with the next available less extreme observation.[98] This procedure was applied to indicator numbers 3, 4, 8, 15–19, and 23 (for indicator numbers see Table 2).

We performed cluster analysis in the 23-dimensional data space using a partitioning algorithm (k-means).[36] We determined the optimal number of clusters by investigating the stability of cluster partitions based on stochastic initialization.[36,99] We repeated the clustering with varying starting points and compared results in a pairwise way. Using 200 comparisons (400 cluster runs), we calculated the share of grid cells that were categorized in the same cluster considering partitions with 2–30 clusters. Results are expressed as consistency measure. Using the same approach of clustering with varying starting points, we calculated the reproduction share of archetype membership for each grid cell based on 200 repetitions of partitions with the optimal cluster number. Moreover, we estimated the indicators‘ importance for the optimal cluster partition by assessing the partition's sensitivity to the omission of indicators, expressed as Fraiman Index[29] (see Figure S4). Low values of the Fraiman Index portray important indicators (i.e., large difference between partitions with original and omitted indicators), while high values depict less important indicators. The Fraiman Index provided a hint on the most important indicators at the level of the entire cluster partition, whereas the average values of indicators at the cluster centers presented the basis for discussing archetype-specific mechanisms. We performed all statistical analyses using the open-source statistics environment R (version 3.5.1).[100]

Policy tailoring

Tailoring policy targets to current levels of biodiversity intactness and threats, food security and agricultural land use is critical for effective reconciliation actions.[18] Clearly, integrated spatial planning in biodiversity-inclusive and participatory ways is required on all land (GBF Target 1). Yet understanding specific regional opportunities and challenges will be key to simultaneously enhance biodiversity, food security, and sustainable land use. We used the social-ecological insights revealed by the human-nature archetypes to tailor selected GBF targets.

We illustrate the tailoring approach by focusing on the interface between farmland biodiversity and agriculture.[18] Overall, integrated spatial planning enshrined in GBF Target 1 (Plan and manage all areas to reduce biodiversity loss) is taken as a global necessity. In addition, we selected three focal approaches capturing nature conservation defined in GBF Target 3 (Conserve 30% of land, waters, and seas), ecological restoration framed in GBF Target 2 (Restore 30% of all degraded ecosystems), and ecological intensification specifically addressing agriculture outlined in GBF Target 10 (Enhance biodiversity and sustainability in agriculture, aquaculture, fisheries, and forestry). The selected approaches depict a broad division between (1) conserving non-use values of biodiversity and (2) restoring ecosystems and re-enhancing ecosystem services such as nutrient cycling, pollination, and natural pest regulation.

To tailor the GBF targets, we prioritized the selected approaches in those regions where they can best support the objectives of reducing biodiversity threats while meeting people's food and livelihood needs.[18] On the one hand, integrated spatial planning focused on nature conservation (GBF Targets 1 and 3) is most effective in archetypes with best-maintained biodiversity and extensively used agricultural areas that can provide substitutes for natural habitats and in archetypes with a high level of endemicity. It emphasizes the protection of remaining species and habitat diversity and exceptional concentrations of endemic species. On the other hand, ecological restoration and ecological intensification shift the perspective toward recovering and re-enhancing functional biodiversity. Integrated spatial planning focused on ecological restoration (GBF Targets 1 and 2) entails active intervention to assist the recovery of degraded, damaged, or destroyed ecosystems.[46] This is most effective in archetypes with low and lowest biodiversity intactness, intensive agriculture, and land-use change threatening remaining biodiversity. In contrast, integrated spatial planning emphasizing ecological intensification (GBF Targets 1 and 10) draws attention to introducing or fostering biodiversity-friendly agricultural practices, replacing external inputs and enhancing productivity.[48,49] It rests on the inclusion of regulating and supporting ecosystem services in agricultural management. Prioritizing this approach in archetypes with intermediate levels of biodiversity intactness and agricultural intensity as well as limited food security is well suited to create and harness synergies between ecosystem services and food security. Based on this attribution, we assessed the regional distribution of prioritized approaches and evaluated the underpinning social-ecological conditions to shed light on particular reconciliation opportunities and challenges.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Diana Sietz (diana.sietz@thuenen.de).

Materials availability

This study did not generate new unique materials.

Data and code availability

The human-nature archetype data generated in this study may be found at https://doi.org/10.5281/zenodo.10851971 under a creative commons attribution (CC-BY) license. The code used in our analysis will also be made available on request under a creative commons attribution – noncommercial (CC-BY-NC) license. All data are available in the main text or the supplemental information.

ACKNOWLEDGMENTS

This research was conducted in the project “Toward a future sustainable world where climate, biodiversity and human well-being are safeguarded” (SustainCBW), funded by the Leibniz Association, Germany (grant number SAS-2017-PIK-LFV). We thank the project partners and all experts who participated in the project workshops for constructive discussions, and Andy Purvis, Odirilwe Selomane, Prajal Pradhan, and Ruth Delzeit for providing comments on an early draft of this paper. We thank Ricardo Gonzalez, Samantha Hill, Richard Fuchs, Katharina Waha, Marrio Herrero, and Prajal Pradhan for providing data; Sebastian Hunger for data preparation; and Stephen Garnett for reviewing and confirming the proper use of the spatial layer on Indigenous Peoples' land. This paper contributes to the GLP Science Plan (Global Land Program, https://glp.earth).

AUTHOR CONTRIBUTIONS

Conceptualization, D.S.; methodology, D.S., A.N., D.M., T.H., K.K., D.D.M., and K.T.; formal analysis, D.S.; visualization, D.S., A.N., and K.T.; writing – original draft, D.S.; writing – review & editing, D.S., A.N., D.M., T.H., K.K., D.D.M., and K.T.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2025.101416.

Received: June 19, 2024
Revised: December 23, 2024
Accepted: July 17, 2025
Published: August 15, 2025

REFERENCES

1. Humboldt, A.V. (1845). Kosmos. Entwurf einer physischen Weltbeschreibung (Cosmos: A Sketch of a Physical Description of the Universe (Gotta'scher Verlag).
2. IPBES (2024). Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Harrison P.A., McElwee P.D., van Huysen T.L., eds. IPBES secretariat). https://doi.org/10.5281/zenodo.13850054.
3. Liu, J., Hull, V., Godfray, H.C.J., Tilman, D., Gleick, P., Hoff, H., Pahl-Wostl, C., Xu, Z., Chung, M.G., Sun, J., and Li, S. (2018). Nexus approaches to global sustainable development. Nat. Sustain. *1*, 466–476. https://doi.org/10.1038/s41893-018-0135-8.
4. IPBES (2019). Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services, E.S. Brondízio, J. Settele, S. Díaz, and H.T. Ngo, eds. (IPBES secretariat) https://zenodo.org/records/6417333.
5. International Union for Conservation of Nature. (2017). The IUCN Red List of Threatened Species. Version 2017-1, http://www.iucnredlist.org.
6. Diaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Agard, J., Arneth, A., Balvanera, P., Brauman, K.A., Butchart, S.H.M., Chan, K.M., et al. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. Science *366*, eaax3100. https://doi.org/10.1126/science.aax31.
7. Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D.E., Coscieme, L., Golden, A.S., Guerra, C.A., Jacob, U., Takahashi, Y., Settele, J., et al. (2022). The direct drivers of recent global anthropogenic biodiversity loss. Sci. Adv. *8*, eabm9982. https://doi.org/10.1126/sciadv.abm9982.
8. Ellis, E.C. (2024). The Anthropocene Condition: Evolving through Social-Ecological Transformations. Philos. Trans. R. Soc. Lond. B Biol. Sci. *379*, 20220255. https://doi.org/10.1098/rstb.2022.0255.
9. Sietz, D., and Neudert, R. (2022). Taking stock of and advancing knowledge on interaction archetypes at the nexus between land, biodiversity, food and climate. Environ. Res. Lett. *17*, 113004. https://doi.org/10.1088/1748-9326/ac9a5c.
10. Bowler, D.E., Bjorkman, A.D., Dornelas, M., Myers-Smith, I.H., Navarro, L.M., Niamir, A., Supp, S.R., Waldock, C., Winter, M., Vellend, M., et al. (2020). Mapping human pressures on biodiversity across the planet uncovers anthropogenic threat complexes. People Nat. *2*, 380–394. https://doi.org/10.1002/pan3.10071.
11. Ellis, E.C., and Ramankutty, N. (2008). Putting People in the Map: Anthropogenic Biomes of the World. Front. Ecol. Environ. *6*, 439–447. https://doi.org/10.1890/070062.
12. Ellis, E.C., Gauthier, N., Klein Goldewijk, K., Bliege Bird, R., Díaz, S., Díaz, S., Fuller, D.Q., Gill, J.L., Kaplan, J.O., Kingston, N., et al. (2021). People have shaped most of terrestrial nature for at least 12,000 years. Proc. Natl. Acad. Sci. USA *118*, e2023483118. https://doi.org/10.1073/pnas.2023483118.
13. Hoang, N.T., Taherzadeh, O., Ohashi, H., Yonekura, Y., Nishijima, S., Yamabe, M., Matsui, T., Matsuda, H., Moran, D., and Kanemoto, K. (2023). Mapping potential conflicts between global agriculture and terrestrial conservation. Proc. Natl. Acad. Sci. USA *120*, e2208376120. https://doi.org/10.1073/pnas.2208376120.
14. Kastner, T., Chaudhary, A., Gingrich, S., Marques, A., Persson, U.M., Bidoglio, G., Le Provost, G., and Schwarzmüller, F. (2021). Global agricultural trade and land system sustainability: Implications for ecosystem carbon storage, biodiversity, and human nutrition. One Earth *4*, 1425–1443. https://doi.org/10.1016/j.oneear.2021.09.006.
15. United Nations Convention on Biological Diversity. (2022). Kunming-Montreal Global Biodiversity Framework. CBD/COP/15/L.25, Montreal, Canada. https://www.cbd.int/doc/c/e6d3/cd1d/daf663719a03902a9b116c34/cop-15-l-25-en.pdf.
16. United Nations Convention on Biological Diversity. (2022). Monitoring framework for the Kunming-Montreal Global Biodiversity Framework. CBD/COP/DEC/15/5, COP15, Montreal, Canada. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-05-en.pdf.
17. United Nations (2015). Transforming our world: the 2030 Agenda for Sustainable Development. In Resolution adopted by the General Assembly on 25 September 2015. A/RES/70/1. https://sdgs.un.org/2030agenda.
18. Sietz, D., Klimek, S., and Dauber, J. (2022). Tailored pathways toward revived farmland biodiversity can inspire agroecological action and policy to transform agriculture. Commun. Earth Environ. *3*, 211. https://doi.org/10.1038/s43247-022-00527-1.
19. Oberlack, C., Pedde, S., Piemontese, L., Václavík, T., and Sietz, D. (2023). Archetypes in support of tailoring land-use policies. Environ. Res. Lett. *18*, 060202. https://doi.org/10.1088/1748-9326/acd802.
20. Halpern, B.S., Boettiger, C., Dietze, M.C., Gephart, J.A., Gonzalez, P., Grimm, N.B., Groffman, P.M., Gurevitch, J., Hobbie, S.E., Komatsu, K. J., et al. (2023). Priorities for Synthesis Research in Ecology and Environmental Science. Ecosphere *14*, e4342. https://doi.org/10.1002/ecs2.4342.
21. Oberlack, C., Sietz, D., Bürgi Bonanomi, E., De Bremond, A., Dell'Angelo, J., Eisenack, K., Ellis, E.C., Epstein, G., Giger, M., Heinimann, A., et al. (2019). Archetype analysis in sustainability research: meanings, motivations, and evidence-based policy making. Ecol. Soc. *24*, 26. https://doi.org/10.5751/ES-10747-240226.
22. Levin, S., Xepapadeas, T., Crépin, A.S., Norberg, J., de Zeeuw, A., Folke, C., Hughes, T., Arrow, K., Barrett, S., Daily, G., et al. (2013). Social-ecological systems as complex adaptive systems: modeling and policy implications. Environ. Dev. Econ. *18*, 111–132. https://doi.org/10.1017/S1355770X12000460.
23. Sietz, D., Frey, U., Roggero, M., Gong, Y., Magliocca, N., Tan, R., Janssen, P., and Václavík, T. (2019). Archetype analysis in sustainability research: methodological portfolio and analytical frontiers. Ecol. Soc. *24*, 34. https://doi.org/10.5751/ES-11103-240334.
24. Sitas, N., Harmáčková, Z.V., Anticamara, J.A., Arneth, A., Badola, R., Biggs, R., Blanchard, R., Brotons, L., Cantele, M., Coetzer, K., et al. (2019). Exploring the usefulness of scenario archetypes in science-policy processes: experience across IPBES assessments. Ecol. Soc. *24*, 35. https://doi.org/10.5751/ES-11039-240335.
25. Jäger, J., Kok, M., Mohamed-Katerere, J.C., Karlsson, S.I., Lüdeke, M.K.B., Dabelko, G.D., Thomalla, F., de Soysa, I., Chenje, M., Filcak, R., et al. (2007). Vulnerability of people and the environment: Challenges and opportunities. In Global Environment Outlook: Environment for development (GEO-4) (United Nations Environment Programme), pp. 301–360.
26. Hill, S.L.L., Gonzalez, R., Sanchez-Ortiz, K., Caton, E., Espinoza, F., Newbold, T., Tylianakis, J., Scharlemann, J.P.W., De Palma, A., and Purvis, A. (2018). Worldwide impacts of past and projected future

land-use change on local species richness and the Biodiversity Intactness Index. Preprint at bioRxiv. https://doi.org/10.1101/311787.

27. Garnett, S.T., Burgess, N.D., Fa, J.E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C.J., Watson, J.E.M., Zander, K.K., Austin, B., Brondizio, E. S., et al. (2018). A spatial overview of the global importance of Indigenous lands for conservation. Nat. Sustain. *1*, 369–374. https://doi.org/10.1038/s41893-018-0100-6.
28. International Labour Organisation. (1989). C169 – Indigenous and Tribal Peoples Convention (No. 169). http://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100_ILO_CODE:C169.
29. Fraiman, R., Justel, A., and Svarc, M. (2008). Selection of variables for cluster analysis and classification rules. J. Am. Stat. Assoc. *103*, 1294–1303. https://doi.org/10.1198/016214508000000544.
30. Locke, H., Ellis, E.C., Venter, O., Schuster, R., Ma, K., Shen, X., Woodley, S., Kingston, N., Bhola, N., Strassburg, B.B.N., et al. (2019). Three global conditions for biodiversity conservation and sustainable use: an implementation framework. Natl. Sci. Rev. *6*, 1080–1082. https://doi.org/10.1093/nsr/nwz136.
31. Eliazer Nelson, A.R.L., Ravichandran, K., and Antony, U. (2019). The impact of the Green Revolution on indigenous crops of India. J. Ethn. Food. *6*, 8. https://doi.org/10.1186/s42779-019-0011-9.
32. Aditya, V., Sumashini, P.S., Aravind, N.A., Ravikanth, G., Krishnappa, C., and Uma Shaanker, R. (2020). Reconciling biodiversity conservation with agricultural intensification: challenges and opportunities for India. Curr. Sci. *118*, 1870–1873.
33. Priyadarshini, P., and Abhilash, P.C. (2020). Policy recommendations for enabling transition towards sustainable agriculture in India. Land Use Policy *96*, 104718. https://doi.org/10.1016/j.landusepol.2020.104718.
34. Tougiani, A., Guero, C., and Rinaudo, T. (2009). Community mobilisation for improved livelihoods through tree crop management in Niger. Geojournal *74*, 377–389. https://doi.org/10.1007/s10708-008-9228-7.
35. Moussa, B., Nkonya, E., Meyer, S., Kato, E., Johnson, T., and Hawkins, J. (2016). Economics of Land Degradation and Improvement in Niger. In Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development, E. Nkonya, A. Mirzabaev, and J. von Braun, eds. (Springer), pp. 499–539.
36. Sietz, D., Ordoñez, J.C., Kok, M.T.J., Janssen, P., Hilderink, H.B.M., Tittonell, P., and Van Dijk, H. (2017). Nested archetypes of vulnerability in African drylands: Where lies potential for sustainable agricultural intensification? Environ. Res. Lett. *12*, 095006. https://doi.org/10.1088/1748-9326/aa768b.
37. Binam, J.N., Place, F., Kalinganire, A., Hamade, S., Boureima, M., Tougiani, A., Dakouo, J., Mounkoro, B., Diaminatou, S., Badji, M., et al. (2015). Effects of farmer managed natural regeneration on livelihoods in semi-arid West Africa. Environ. Econ. Policy Stud. *17*, 543–575. https://doi.org/10.1007/s10018-015-0107-4.
38. Bennett, E.M., Solan, M., Biggs, R., McPhearson, T., Norström, A.V., Olsson, P., Pereira, L., Peterson, G.D., Raudsepp-Hearne, C., Biermann, F., et al. (2016). Bright spots: seeds of a good Anthropocene. Front. Ecol. Environ. *14*, 441–448. https://doi.org/10.1002/fee.1309.
39. Zalles, V., Hansen, M.C., Potapov, P.V., Parker, D., Stehman, S.V., Pickens, A.H., Parente, L.L., Ferreira, L.G., Song, X.P., Hernandez-Serna, A., and Kommareddy, I. (2021). Rapid expansion of human impact on natural land in South America since 1985. Sci. Adv. *7*, eabg1620.
40. Pacheco, A., and Meyer, C. (2022). Land tenure drives Brazil's deforestation rates across socio-environmental contexts. Nat. Commun. *13*, 5759. https://doi.org/10.1038/s41467-022-33398-3.
41. Gibbs, H.K., Rausch, L., Munger, J., Schelly, I., Morton, D.C., Noojipady, P., Soares-Filho, B., Barreto, P., Micol, L., and Walker, N.F. (2015). Brazil's soy moratorium. Science *347*, 377–378. https://doi.org/10.1126/science.aaa0181.
42. Soterroni, A.C., Ramos, F.M., Mosnier, A., Fargione, J., Andrade, P.R., Baumgarten, L., Pirker, J., Obersteiner, M., Kraxner, F., Câmara, G., et al. (2019). Expanding the Soy Moratorium to Brazil's Cerrado. Sci. Adv. *5*, eaav7336. https://doi.org/10.1126/sciadv.aav7336.
43. United Nations Convention on Biological Diversity (2010). The Strategic Plan for Biodiversity 2011–2020 and the Aichi Biodiversity Targets (United Nations Convention on Biological Diversity). https://www.cbd.int/sp.
44. Shen, X., Liu, M., Hanson, J.O., Wang, J., Locke, H., Watson, J.E.M., Ellis, E.C., Li, S., and Ma, K. (2023). Countries' differentiated responsibilities to fulfil area-based conservation targets of the Kunming-Montreal Global Biodiversity Framework. One Earth *6*, 548–559. https://doi.org/10.1016/j.oneear.2023.04.007.
45. Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental change. Glob. Environ. Change *20*, 550–557. https://doi.org/10.1016/j.gloenvcha.2010.07.004.
46. Society for Ecological Restoration International Science. (2004). The SER International Primer on Ecological Restoration (Society for Ecological Restoration International Science & Policy Working Group, www.ser.org&Tucson).
47. Gann, G.D., McDonald, T., Walder, B., Aronson, J., Nelson, C.R., Jonson, J., Hallett, J.G., Eisenberg, C., Guariguata, M.R., Liu, J., et al. (2019). International principles and standards for the practice of ecological restoration. Restor. Ecol. *27*, S1–S46. https://doi.org/10.1111/rec.13035.
48. Bommarco, R., Kleijn, D., and Potts, S.G. (2013). Ecological intensification: harnessing ecosystem services for food security. Trends Ecol. Evol. *28*, 230–238. https://doi.org/10.1016/j.tree.2012.10.012.
49. Kleijn, D., Bommarco, R., Fijen, T.P.M., Garibaldi, L.A., Potts, S.G., and van der Putten, W.H. (2019). Ecological Intensification: Bridging the Gap between Science and Practice. Trends Ecol. Evol. *34*, 154–166. https://doi.org/10.1016/j.tree.2018.11.002.
50. High Level Panel of Experts for Food Security and Nutrition. (2019). Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems That Enhance Food Security and Nutrition. https://www.fao.org/agroecology/database/detail/en/c/1242141.
51. Barrios, E., Gemmill-Herren, B., Bicksler, A., Siliprandi, E., Brathwaite, R., Moller, S., Batello, C., and Tittonell, P. (2020). The 10 Elements of Agroecology: Enabling transitions towards sustainable agriculture and food systems through visual narratives. Ecosyst. Peopl. *16*, 230–247. https://doi.org/10.1080/26395916.2020.1808705.
52. Pilling, D., Bélanger, J., and Hoffmann, I. (2020). Declining biodiversity for food and agriculture needs urgent global action. Nat. Food *1*, 144–147. https://doi.org/10.1038/s43016-020-0040-y.
53. Wanger, T.C., DeClerck, F., Garibaldi, L.A., Ghazoul, J., Kleijn, D., Klein, A.M., Kremen, C., Mooney, H., Perfecto, I., Powell, L.L., et al. (2020). Integrating agroecological production in a robust post-2020 Global Biodiversity Framework. Nat. Ecol. Evol. *4*, 1150–1152. https://doi.org/10.1038/s41559-020-1262-y.
54. Dou, Y., Cosentino, F., Malek, Z., Maiorano, L., Thuiller, W., and Verburg, P.H. (2021). A new European land systems representation accounting for landscape characteristics. Landsc. Ecol. *36*, 2215–2234. https://doi.org/10.1007/s10980-021-01227-5.
55. Garibaldi, L.A., Oddi, F.J., Miguez, F.E., Bartomeus, I., Orr, M.C., Jobbágy, E.G., Kremen, C., Schulte, L.A., Hughes, A.C., Bagnato, C., et al. (2021). Working landscapes need at least 20% native habitat. Conserv. Lett. *14*, e12773. https://doi.org/10.1111/conl.12773.
56. Concepcion, E.D., and Díaz, M. (2019). Varying potential of conservation tools of the Common Agricultural Policy for farmland bird preservation. Sci. Total Environ. *694*, 133618. https://doi.org/10.1016/j.scitotenv.2019.133618.

57. Piemontese, L., Neudert, R., Oberlack, C., Pedde, S., Roggero, M., Buchadas, A., Martin, D.A., Orozco, R., Pellowe, K., Segnon, A.C., et al. (2022). Validity and validation in archetype analysis: practical assessment framework and guidelines. Environ. Res. Lett. *17*, 025010. https://doi.org/10.1088/1748-9326/ac4f12.
58. Reyers, B., and Selig, E.R. (2020). Global targets that reveal the social-ecological interdependencies of sustainable development. Nat. Ecol. Evol. *4*, 1011–1019. https://doi.org/10.1038/s41559-020-1230-6.
59. Pimm, S.L., Jenkins, C.N., Abell, R., Brooks, T.M., Gittleman, J.L., Joppa, L.N., Raven, P.H., Roberts, C.M., and Sexton, J.O. (2014). The biodiversity of species and their rates of extinction, distribution, and protection. Science *344*, 1246752. https://doi.org/10.1126/science.1246752.
60. BirdLife International (2017). Handbook of the Birds of the World. In Bird species distribution maps of the world Version 6.0. http://datazone.birdlife.org/species/requestdis.
61. Collen, B., Whitton, F., Dyer, E.E., Baillie, J.E.M., Cumberlidge, N., Darwall, W.R.T., Pollock, C., Richman, N.I., Soulsby, A.M., and Böhm, M. (2014). Global patterns of freshwater species diversity, threat and endemism. Glob. Ecol. Biogeogr. *23*, 40–51. https://doi.org/10.1111/geb.12096.
62. Selig, E.R., Turner, W.R., Troëng, S., Wallace, B.P., Halpern, B.S., Kaschner, K., Lascelles, B.G., Carpenter, K.E., and Mittermeier, R.A. (2014). Global Priorities for Marine Biodiversity Conservation. PLoS One *9*, e82898. https://doi.org/10.1371/journal.pone.0082898.
63. Kreft, H., and Jetz, W. (2007). Global patterns and determinants of vascular plant diversity. Proc. Natl. Acad. Sci. USA *104*, 5925–5930. https://doi.org/10.1073/pnas.0608361104.
64. Moran, D., and Kanemoto, K. (2017). Identifying species threat hotspots from global supply chains. Nat. Ecol. Evol. *1*, 23. https://doi.org/10.1038/s41559-016-0023.
65. Fuchs, R., Prestele, R., and Verburg, P.H. (2018). A global assessment of gross and net land change dynamics for current conditions and future scenarios. Earth Syst. Dynam. *9*, 441–458. https://doi.org/10.5194/esd-9-441-2018.
66. Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., et al. (2017). An assessment of the global impact of 21st century land use change on soil erosion. Nat. Commun. *8*, 2013. https://doi.org/10.1038/s41467-017-02142-7.
67. Center for International Earth Science Information Network (2021). Global Subnational Infant Mortality Rates, Version 2.01 (NASA Socioeconomic Data and Applications Center (SEDAC) (Palisades)). https://doi.org/10.7927/0gdn-6y33.
68. Pradhan, P., Lüdeke, M.K.B., Reusser, D.E., and Kropp, J.P. (2014). Food Self-Sufficiency across Scales: How Local Can We Go? Environ. Sci. Technol. *48*, 9463–9470. https://doi.org/10.1021/es5005939.
69. Pradhan, P., Kriewald, S., Costa, L., Rybski, D., Benton, T.G., Fischer, G., and Kropp, J.P. (2020). Urban food systems: how regionalization can contribute to climate change mitigation. Environ. Sci. Technol. *54*, 10551–10560. https://doi.org/10.1021/acs.est.0c02739.
70. Kummu, M., Taka, M., and Guillaume, J.H.A. (2018). Gridded global datasets for Gross Domestic Product and Human Development Index over 1990–2015. Sci. Data *5*, 180004. https://doi.org/10.1038/sdata.2018.4.
71. Herrero, M., Thornton, P.K., Power, B., Bogard, J.R., Remans, R., Fritz, S., Gerber, J.S., Nelson, G., See, L., Waha, K., et al. (2017). Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planet. Health *1*, e33–e42. https://doi.org/10.1016/S2542-5196(17)30007-4.
72. Food and Agriculture Organization of the United Nations, and International Institute for Applied Systems Analysis. (2021). Global Agro-Ecological Zones (GAEZ v4) – Data Portal user's guide. https://doi.org/10.4060/cb5167en.
73. Klein Goldewijk, K., Beusen, A., Doelman, J., and Stehfest, E. (2017). Anthropogenic land use estimates for the Holocene – HYDE 3.2. Earth Syst. Sci. Data *9*, 927–953. https://doi.org/10.5194/essd-9-927-2017.
74. Lu, C., and Tian, H. (2016). Half-degree Gridded Nitrogen and Phosphorus Fertilizer Use for Global Agriculture Production during 1900–2013 (PANGAEA). https://doi.org/10.1594/PANGAEA.863323.
75. Xu, R., Tian, H., Pan, S., Dangal, R.S.S., Chen, J., Chang, J., Lu, Y., Skiba, U.M., Tubiello, F., and Zhang, B. (2018). Half-degree Gridded Manure and Fertilizer Nitrogen Inputs in Global Grassland Systems during 1860–2016 (PANGAEA). https://doi.org/10.1594/PANGAEA.892940.
76. World Bank. (2019). Worldwide Governance Indicators. http://info.worldbank.org/governance/wgi/#home.
77. Weiss, D.J., Nelson, A., Gibson, H.S., Temperley, W., Peedell, S., Lieber, A., Hancher, M., Poyart, E., Belchior, S., Fullman, N., et al. (2018). A global map of travel time to cities to assess inequalities in accessibility in 2015. Nature *553*, 333–336. https://doi.org/10.1038/nature25181.
78. Center for International Earth Science Information Network (2018). Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11 (NASA Socioeconomic Data and Applications Center (SEDAC) (Palisades)). https://doi.org/10.7927/H49C6VHW.
79. Scholes, R.J., and Biggs, R. (2005). A biodiversity intactness index. Nature *434*, 45–49. https://doi.org/10.1038/nature03289.
80. Newbold, T., Hudson, L.N., Arnell, A.P., Contu, S., De Palma, A., Ferrier, S., Hill, S.L.L., Hoskins, A.J., Lysenko, I., Phillips, H.R.P., et al. (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science *353*, 288–291. https://doi.org/10.1126/science.aaf2201.
81. Purvis, A., Newbold, T., De Palma, A., Contu, S., Hill, S.L.L., Sanchez-Ortiz, K., Phillips, H.R.P., Hudson, L.N., Lysenko, I., Börger, L., and Scharlemann, J.P.W. (2018). Chapter Five – Modelling and Projecting the Response of Local Terrestrial Biodiversity Worldwide to Land Use and Related Pressures: The PREDICTS Project. In Advances in Ecological Research, D.A. Bohan, A.J. Dumbrell, G. Woodward, and M. Jackson, eds. (Academic Press), pp. 201–241.
82. Tilman, D., Clark, M., Williams, D.R., Kimmel, K., Polasky, S., and Packer, C. (2017). Future threats to biodiversity and pathways to their prevention. Nature *546*, 73–81. https://doi.org/10.1038/nature22900.
83. Di Marco, M., Venter, O., Possingham, H.P., and Watson, J.E.M. (2018). Changes in human footprint drive changes in species extinction risk. Nat. Commun. *9*, 4621. https://doi.org/10.1038/s41467-018-07049-5.
84. Howard, C., Flather, C.H., and Stephens, P.A. (2020). A global assessment of the drivers of threatened terrestrial species richness. Nat. Commun. *11*, 993. https://doi.org/10.1038/s41467-020-14771-6.
85. Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., and Geschke, A. (2012). International trade drives biodiversity threats in developing nations. Nature *486*, 109–112. https://doi.org/10.1038/nature11145.
86. Food and Agriculture Organization of the United Nations, and United Nations Environment Programme (2020). The State of the World's Forests 2020: Forests, Biodiversity and People (FAO, UNEP). https://doi.org/10.4060/ca8642en.
87. Tscharntke, T., Grass, I., Wanger, T.C., Westphal, C., and Batáry, P. (2021). Beyond organic farming-harnessing biodiversity-friendly landscapes. Trends Ecol. Evol. *36*, 919–930. https://doi.org/10.1016/j.tree.2021.06.010.
88. Pendrill, F., Gardner, T.A., Meyfroidt, P., Persson, U.M., Adams, J., Azevedo, T., Bastos Lima, M.G., Baumann, M., Curtis, P.G., De Sy, V., et al. (2022). Disentangling the numbers behind agriculture-driven tropical deforestation. Science *377*, eabm9267. https://doi.org/10.1126/science.abm9267.
89. Food and Agriculture Organization of the United Nations. (2000). Guidelines for national FIVIMS. Background and principles. www.fao.org/docrep/003/X8346E/X8346E00.HTM.

90. Beyene, S.D. (2023). The impact of food insecurity on health outcomes: empirical evidence from sub-Saharan African countries. BMC Public Health *23*, 338. https://doi.org/10.1186/s12889-023-15244-3.

91. Cassidy-Vu, L., Way, V., and Spangler, J. (2022). The correlation between food insecurity and infant mortality in North Carolina. Public Health Nutr. *25*, 1038–1044. https://doi.org/10.1017/S136898002200026X.

92. Ritchie, H., and Roser, M. (2019). Land use. How is humanity using the Earth's land? And how can we decrease our land use so that more land is left for wildlife? First published in September 2019. https://ourworldindata.org/land-use.

93. Jones, S.K., Sánchez, A.C., Beillouin, D., Juventia, S.D., Mosnier, A., Remans, R., and Estrada Carmona, N. (2023). Achieving win-win outcomes for biodiversity and yield through diversified farming. Basic Appl. Ecol. *67*, 14–31. https://doi.org/10.1016/j.baae.2022.12.005.

94. Kaufmann, D., Kraay, A., and Mastruzzi, M. (2010). The Worldwide Governance Indicators: Methodology and Analytical Issues. Policy Research working paper, No. WPS 5430. http://hdl.handle.net/10986/3913.

95. Sietz, D., Mamani Choque, S.E., and Lüdeke, M.K.B. (2012). Typical patterns of smallholder vulnerability to weather extremes with regard to food security in the Peruvian Altiplano. Reg. Environ. Change *12*, 489–505. https://doi.org/10.1007/s10113-011-0246-5.

96. Kastner, T., Matej, S., Forrest, M., Gingrich, S., Haberl, H., Hickler, T., Krausmann, F., Lasslop, G., Niedertscheider, M., Plutzar, C., et al. (2022). Land use intensification increasingly drives the spatiotemporal patterns of the global human appropriation of net primary production in the last century. Glob. Chang. Biol. *28*, 307–322. https://doi.org/10.1111/gcb.15932.

97. World Bank. (2019). World Development Indicators. https://databank.worldbank.org/reports.aspx?source=2&series=NV.AGR.TOTL.ZS&country=#

98. Barnett, V., and Lewis, T. (1994). Outliers in Statistical Data, 3rd Ed. (Wiley).

99. Janssen, P., Walther, C., and Lüdeke, M.K.B. (2012). Cluster analysis to understand socio-ecological systems: a guideline (PIK Report, Potsdam Institute for Climate Impact Research).

100. R Core Team (2021). R: A Language and Environment for Statistical Computing (R Foundation for Statistical Computing). https://www.R-project.org/.