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Avoiding an unjust transition to sustainability: An equity metric for spatial conservation planning

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The need for rapid and ambitious conservation and restoration is widely acknowledged, yet concern exists that the widespread reallocation of land to nature would disproportionately affect the world's poor. Conservation and restoration may limit nutrition and livelihood options and thus negatively affect social development objectives. Although much research looks into global-scale scenarios and planning of conservation and restoration, spatial evaluations of these trade-offs in terms of equity remain limited. We fill this gap by identifying areas where conservation or restoration under different future scenarios and prioritization maps expand nature into landscapes that likely support land-dependent communities in their local food security. By contrasting the expansion of nature into areas supporting land-dependent communities vs. places where the food system is supported by regional to global markets, we highlight the need for disaggregated indicators that reflect the diversity of human land-use needs in order to identify more equitable pathways. Conservation prioritizations were found to result in more equitable land-use outcomes than the land-use outcomes of widely used socioeconomic scenarios. Accounting for differentiated social impacts in model-based conservation and restoration planning and global scale scenario assessment can help achieve a more inclusive transition to sustainability as well as reduce barriers to meaningful change.

conservation planning | equity | food security

Significance

Vast areas of land are required for future nature conservation and restoration; however, the livelihood needs of people depending on these landscapes are often insufficiently represented in spatial planning frameworks, which can lead to unintended trade-offs with development objectives. We present a systematic approach to identifying areas of potential tension between global conservation objectives and local food security, evaluating the outcome in terms of equity. Hotspots of potential tension are distributed throughout tropical regions, with conservation prioritizations generally more equitable than leading future scenarios. Our results indicate considerable room for more explicit consideration of social land-use needs in conservation planning, which is needed to help ensure more equitable environmental governance.

Mounting fear around the stability of planetary processes that support human well-being has scientists calling for the rapid and widespread conservation and restoration of nature (1–10), leading to increasing ambition in multilateral agreements (11–13). This has stimulated the development of global priority maps which identify the most critical areas for conservation and restoration to achieve global biodiversity and climate goals (5, 7, 8, 14–21). The general congruence among such recommendations has confirmed the importance of certain landscapes, particularly in tropical and subtropical regions (19, 22). Nevertheless, significant resistance to implementation can come from the presence of social and economic tradeoffs (14, 23–30), as land set aside for nature can impede local livelihood options (14, 22, 28, 30–33). Mainstream conservation—stemming historically from Western knowledge systems—has often resulted in the establishment of protected areas that exclude people and their activities from such landscapes (18, 19, 27, 32–40). This has often exacerbated issues of poverty, landlessness, and food insecurity in regions where communities were already marginalized (18, 27, 32, 33, 35, 37, 41–46). While there is now widespread recognition of other more socially inclusive strategies (2, 18, 27, 32, 35–37, 41, 47), early attempts at development-oriented conservation have had mixed results (26, 27, 35, 38, 42, 48), leading to a strong "neo/nature-protectionist" countermovement which advocates for the strict protection of sufficient wilderness (18, 25, 28, 34, 42, 48). This latter perspective has inspired a variety of "Half-Earth" proposals (1, 2, 15, 47, 49, 50), that promote science-based target of protecting at least 50% of the planet (2, 15, 47, 51). Such ambition is certainly necessary; however, this framework could also reinvigorate social justice challenges by reducing livelihood options of inhabitants (6, 8, 19, 22, 25, 29, 33–35, 47, 51–53). While these protectionist proposals do endorse the idea of avoiding social harm (2, 47), they offer little practical guidance on how to accomplish this or navigate the social and political difficulties that would inevitably arise (6, 25, 34, 35, 47, 51).

Top–down target setting and land use planning are often critiqued due to the complex social consequences associated with implementation (25, 47, 54). Nevertheless, such global-scale planning and analysis remains valuable for developing effective solutions to crises that have global consequences and require coordinated action to be effective (17, 22, 55–57). This, however, generates tensions between the coherence of global frameworks and the diverse needs of local communities (22, 58). The way the models are conceptualized often influences how policy goals are defined and translated into land-use outcomes within modeling frameworks (59, 60), and these may not always align with

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locally defined values or needs (22, 58). While many models incorporate human land-use demands such as agriculture in order to find optimized solutions (9, 61), it is not simply global production that matters but also where and by/for whom this food production and distribution is secured (22, 33, 62). Different communities have different relationships with the various food production systems, based on, for instance, access to markets or traditional cultural practices (29, 33, 63). Optimizing the provisioning of different value indicators at a large scale therefore risks masking issues of equity and environmental justice (14, 22).

Equity is a common measure of fairness endorsed by the global community through the principle of Common But Differentiated Responsibilities and Respective Capabilities (64). Simply put, this principle states that those who are less responsible for the problem and less capable of shouldering the cost of the solution should be less responsible for doing so, thereby avoiding disproportionate harm to already vulnerable communities (64). While the reallocation of land used by communities to nature would everywhere have social impacts (positive and negative), we assume that communities who make land-use decisions based on survival and livelihood needs (hereafter Land-Dependent Communities or LandDCs) are unequally affected due to a greater dependence on local land resources for their nutrition (63). In contrast, if communities who rely on global or regional markets for their nutritional security (hereafter Market-Dependent Communities or MarketDCs) lose access to their land then a social cost is still born, but one that is less directly threatening to social well-being as alternative livelihoods are often available. The "cost" of conservation and restoration is therefore in this context defined as the potential opportunity costs caused by either physical displacement or displacement of cultural and economic activities such as subsistence agriculture.

To address this, we explore these tensions by examining whether contemporary scenarios (identifying possible societal trajectories and their impacts on land use) and conservation prioritizations (optimizing biodiversity outcomes), both of which are widely used in the scientific community, facilitate progress toward our global environmental goals in accordance to this definition of equity. In addition, we address the need for better integration of differentiated social values that reflect the needs and capabilities of different communities into global conservation planning and the modeling tools. By contrasting the possible impact of future conservation and restoration—measured as the relative area of land or relative number of people—on LandDCs, against the cost to MarketDCs, we demonstrate one way to evaluate model outputs in terms of equity. If LandDCs are less affected than MarketDCs, then the outcome by our definition is equitable. In addition, we also quantify the food-crop calories that could be put at risk on LandDC land.

Land use scenarios map out likely future trends following projected future demands for food, resources, and space for settlements, which are spatially allocated based on a discrete set of assumptions and decision rules (65). We focus on the Shared Socio-economic Pathways (SSPs) 1, 2, and 3 as simulated by an Integrated Assessment model (66), as well as a Sustainability and Restoration scenario (SSPR) (67). SSP1 represents a "Sustainability Scenario" of improved environmental resource management and social equality and slower economic growth (68). SSP2 represents a "Middle of the Road" scenario based on historical trends, and SSP3 represents "Regional Rivalry" based on interregional competition with growing social inequality and unsustainable resource consumption (68). The "Sustainability and Restoration" modeled land systems in a future where climate and biodiversity targets were achieved and agricultural systems were intensified with meat consumption curbed to meet regional demands (67). The distribution of land systems under the parameters set by each of the storylines was taken from spatially explicit land system scenarios for the year 2050 (66). Evaluating the outcome of these scenarios in terms of equity provides insights around the risks associated with these potential futures, as well as models' assumptions and rules.

Next to the scenarios, we evaluated three global conservation prioritizations, which are planning tools used to select conservation and restoration locations based on the optimization of indicators of conservation value (8, 17, 57). The Remote50% prioritization represents an ecoregion-based approach to the Half-Earth proposal (2, 6, 15, 35, 47, 51), where the least used or most remote land is protected first (27, 47, 51, 69, 70). A second Half-Earth prioritization (PBL50%) was developed using the integrated assessment model IMAGE and the biodiversity model GLOBIO to optimize species functional diversity, climate change mitigation, and global food security (71, 72). While technically modeled as a half-earth scenario, this map focuses on environmental objectives rather than likely socioeconomic trajectories, and so is included as a prioritization (71, 72). Finally, the third prioritization (Top50%) represents the highest 50% of the ranked conservation priorities based on optimization modeling, identifying areas that are the most important for biodiversity, carbon, and freshwater (57). If these spatial outcomes produce an inequitable distribution of tradeoffs with human development, then future conservation planning may hold an obligation to better include an explicit measure of socially disaggregated land-use needs and values as an additional objective to be optimized.

Results

We identify clear patterns for where Land-Dependent (LandDC) and Market-Dependent communities (MarketDC) are most likely to be affected by conservation and restoration of nature (Figs. 1 and 2). LandDC are particularly impacted in sub-Saharan Africa, South, East, and Southeast Asia, as well as parts of Central and South America, while conservation efforts will compete with MarketDCs mostly in eastern North America and Europe (Fig. 1). Layering the results for nature expansion into LandDC areas under each of the scenarios and prioritizations reveals hotspots of potential tension, particularly in sub-Saharan Africa and Asia (Fig. 2).

Comparing the relative impact of land-use change on the different societal groups, we found that generally, the most equitable outcomes resulted from pursuing a science-driven conservation prioritization rather than letting land use be determined by societal trajectories as captured in the scenarios. Loss in access to land was measured in two ways—the relative area of nature expansion into LandDC and MarketDC lands (Fig. 3) and the relative number of people in LandDC and MarketDC lands that would be affected (Fig. 4). LandDC results were complimented with an evaluation of only the Most Vulnerable (hereafter MV) members of this category—Survivalists and Subsistence-Oriented Smallholders (see the *Materials and Methods* section for further explanation). With respect to the relative land area, measured as a proportion of the total area inhabited by each land-user group, the prioritizations result in 31 to 38% of MarketDC lands accommodating nature expansion, as compared to 28 to 33% of LandDC lands or 27 to 32% of land for the Most Vulnerable (Fig. 3 and Table 1). The scenarios are less equitable (but more equal), with roughly 8 to 17% of MarketDC lands, 9 to 16% of LandDC lands, and 8 to 15% of MV lands accommodating nature expansion (Fig. 3 and Table1). Considering geographic realms independently, we see

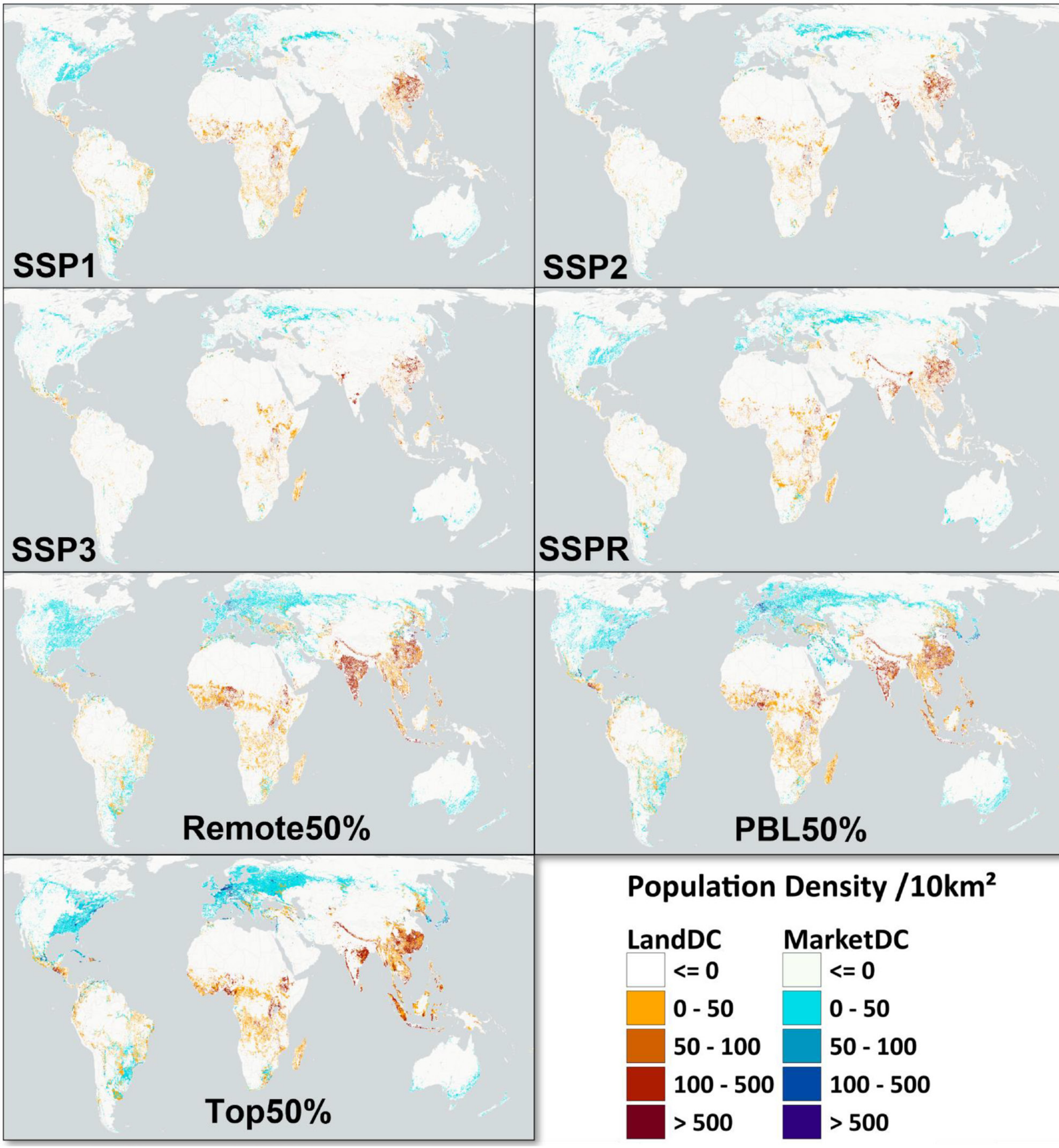

Fig. 1. LandDC and MarketDC population density and distribution in land potentially affected by nature expansion in each of the scenarios and prioritizations.

that a larger proportion of LandDC lands are affected in the Afrotropics across all pathways (4 to 12%), while the largest proportion of MarketDC lands are affected in the Palearctic (4 to 19%) and Nearctic (2 to 11%) in all pathways (Fig. 3).

When considering the relative number of people affected, measured as a proportion of the total subpopulation for each land-user group, only the Top50% and PBL50% prioritizations result in a greater proportion of MarketDC land users paying a greater cost of conservation (47% and 37% of the people living on MarketDC lands, respectively, vs. 37% and 32% of the people living on LandDC lands or 34 and 33% of people in MV lands), while in the Remote50% prioritization and all scenarios, LandDCs are disproportionately burdened (4 to 21% MarketDC vs. 9 to 31% LandDC or 7 to 29% MV) (Fig. 4 and Table1). Examined across geographic realms, the largest proportion of the LandDC population is affected in the Indomalayan realm for all prioritizations (20 to 24%) and almost all scenarios (4 to 7%) (Fig. 4). For MarketDC, the largest proportion of the population is affected in the Palearctic for all prioritizations (17 to 32%) and scenarios (3 to 6%) (Fig. 4). These findings are statistically confirmed using a Chi-squared test of independence. We compared the proportion of affected and unaffected LandDC and MarketDC land users against the frequencies that would be expected if there was no association between decision-making type and being affected by

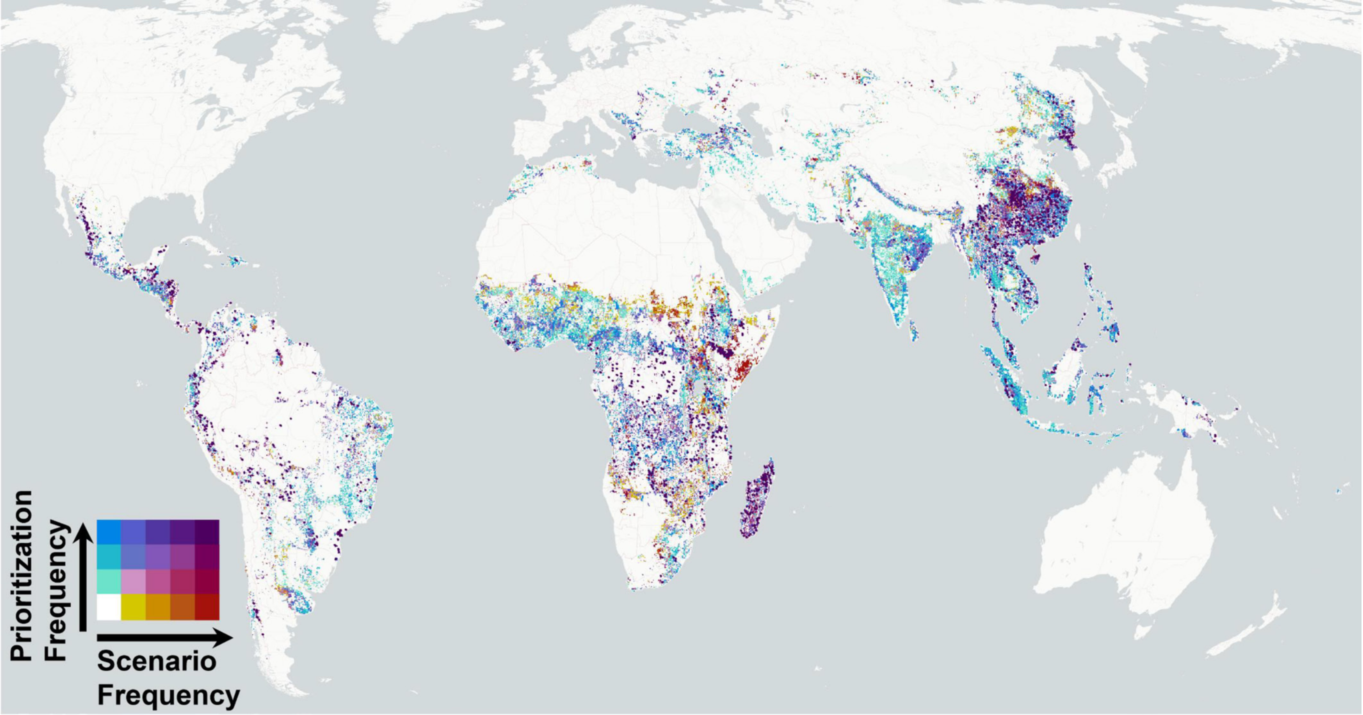

Fig. 2. Regions of potential tension between projected or proposed nature expansion and areas dominated by Land-Dependent Communities. Colors increasing in intensity along the red spectrum indicate frequency with which a pixel is identified in scenarios, while increasing intensity along the blue spectrum indicates prioritization frequency. Purple colors indicate identification in both scenarios and prioritizations.

nature expansion. Every test result is statistically significant ($P <<$ 0.05), indicating that one group is always disproportionately affected.

All scenarios and prioritizations result in decreased nutritional security for a considerable number of people, assuming that implementation would restrict access to land (Fig. 5 and Table1). Nutritional security was defined, for this purpose, as the ability to obtain food from local food systems in landscapes populated by LandDCs. Our results indicate that nature expansion under the scenarios could jeopardize between 340 and 230 trillion calories produced by food crops on LandDC lands, or enough to feed over 446 million people under the SSPR scenario and 310 million under the SSP3 scenario, based on the daily recommended intake of 2,100 calories per day (73) (Fig. 5 and Table 1). For the prioritizations, the Top50% could put at risk 850 trillion food calories produced on LandDC lands, equating to the caloric requirements of over 1 billion people (Fig. 5 and Table 1). The Remote50%, in contrast, threatens 670 trillion on LandDC lands, or enough to feed 871 million people, and the PBL50% 630 trillion calories or 825 million people (Fig. 5 and Table 1).

The variation in outcome among the different pathways enables a comparison of the relationships between social impact and biodiversity outcomes. The ratio between the proportion of LandDC and MarketDC lands affected viewed in relation to the change in extent of natural areas illustrates that the prioritizations are not only more equitable but they also restore more nature. This is particularly in contrast with the SSP1-3 scenarios which project a net loss of natural areas (Fig. 6*A*). We observe similar results when looking at the ratio between the share of people on LandDC and MarketDC lands affected in relation to the change in natural areas. Again the Top50% and PBL50% are the most equitable and restore the most nature. The SSP1-3 scenarios, in contrast, still affect 11 to 17% of people living in areas dominated by LandDCs despite the net loss of nature (Fig. 6*B*). The SSPR scenario on the other hand increases natural areas by over 6 million km^2 while affecting only 18% of the population in LandDC lands, likely due to the way trade-offs were minimized in the model via agricultural intensification and reductions in livestock demand (67). The Remote50% and Top50% achieve a net expansion of 8 to 12 million km^2 but affect 39 to 47% of the people in LandDC lands. The PBL50% prioritization affects 41% of the people on LandDC lands but achieves a net expansion of over 28 million km^2. This dramatic increase in natural extent under the PBL50% may be in part due to the different modeling frameworks and land system classifications used when producing the maps, but also intensification of agricultural systems, reduction in meat producing systems, and expansion of natural vegetation cover into historically sparse landscapes for climate change mitigation (72).

Discussion

We present a global-scale, spatially explicit evaluation of a specific equity concern associated with projected and recommended conservation and restoration efforts. We focused on distributional equity by considering the potential land-use costs to two broad but distinct land-user groups within society: Land-Dependent Communities and Market-Dependent Communities, with equity here defined as LandDC communities paying a relatively smaller share of the opportunity cost. Our results suggest that trade-offs with development objectives and concerns around equitable burden sharing may not be sufficiently considered in many leading global conservation planning efforts or in the assumptions and rules of the models themselves.

Our results should not be interpreted in terms of a “nature vs. development” dichotomy, nor as a way to undermine ambition or debase protected areas as a conservation strategy. Much harm would be generated by failing to restore biodiversity, particularly for communities that rely on ecosystem function and local natural resources

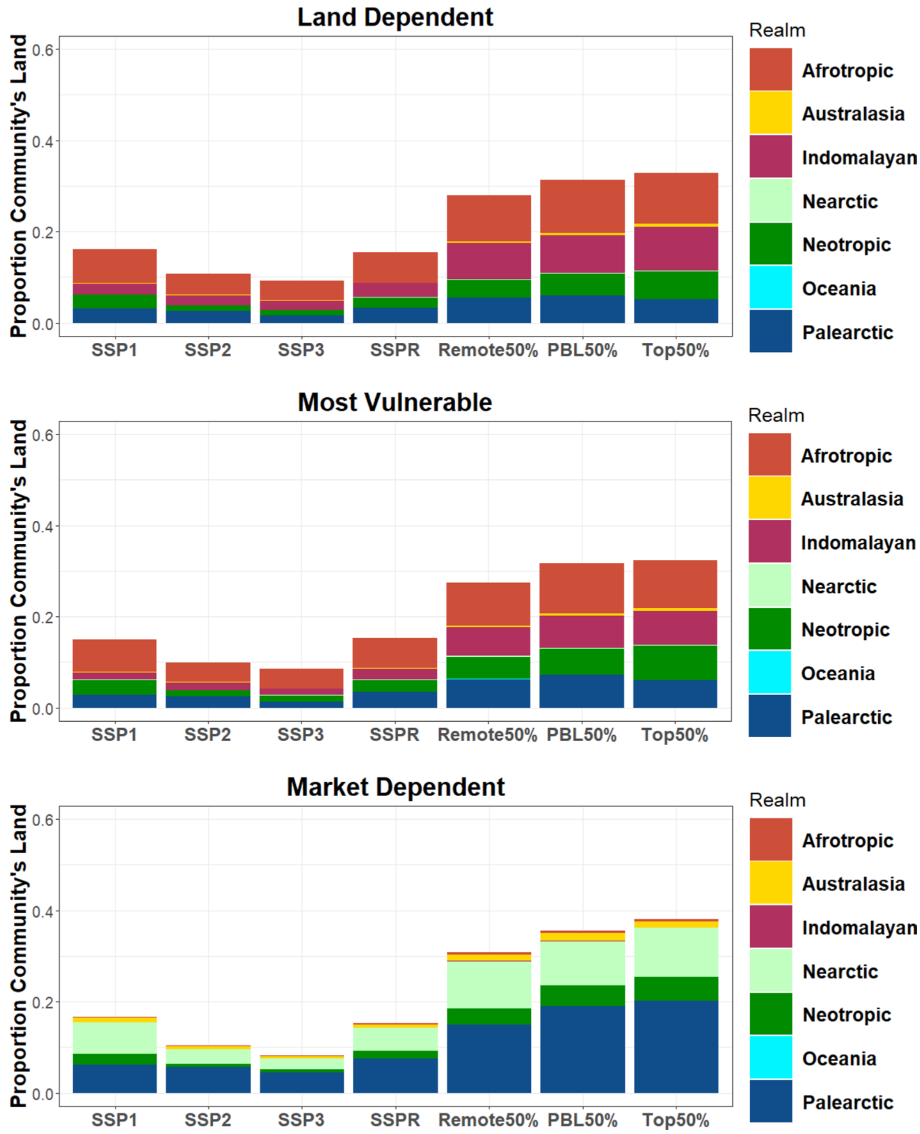

Fig. 3. Relative area of land affected by nature expansion for Land-Dependent Communities, the Most Vulnerable, and Market-Dependent Communities. Values are calculated as the area of overlap between future nature expansion and land inhabited by each decision-making type, divided by the total area inhabited by each group.

for their livelihoods and well-being (14, 33, 74). Rather, we highlight two considerations that are necessary for ensuring that solutions adhere to values of equity. First, accounting for differentiated societal land-use needs in global conservation agendas is necessary to optimize both social and environmental outcomes. Second, modelers need to expand their assumptions on what type of land-use change can be expected in different localities and take into consideration that some areas (while possibly underutilized in terms of agricultural efficiency or restoration potential) are important for groups whose needs are typically underrepresented. This would require improvements in the type and availability of data which can describe these different groups and how they use their land. We provide an example on how to include these considerations in global models by using spatial distributions of dependencies on local land use. By being explicit about assumptions and positionalities, and finding ways to better link model outputs with equity considerations, global models represent a powerful set of tools for identifying suitable options or highlighting risks.

The scenarios consistently performed more poorly along our equity metric as compared to the prioritizations. This may indicate that the dominant socioeconomic trends driving land-use change are likely to override the land-use needs of vulnerable communities irrespective of socioeconomic trajectory (SSP1-3). As the value of scenario development is to test the potential outcomes of different policy pathways, these insights open the space for more transformative scenarios by encouraging modelers to identify key inputs which generate more equitable results. For the prioritizations, the Remote50% prioritization, like the scenarios, also resulted in a disproportionate number of people on LandDC affected, despite prioritizing land with the lowest human footprint. The PBL50% and Top50% prioritizations, while affecting more people overall, resulted in relatively more people living in MarketDCs affected than in LandDCs, thereby aligning with our definition of equity. Overall, these results show that while there have been advancements in the integration of stakeholder engagement into scenario development at national or subnational scales (see ref. 75), there remains considerable scope for including equity in global conservation planning as an additional objective to be achieved.

Existing research has previously highlighted justice concerns associated with ambitious conservation. Pursuing a strict 50%

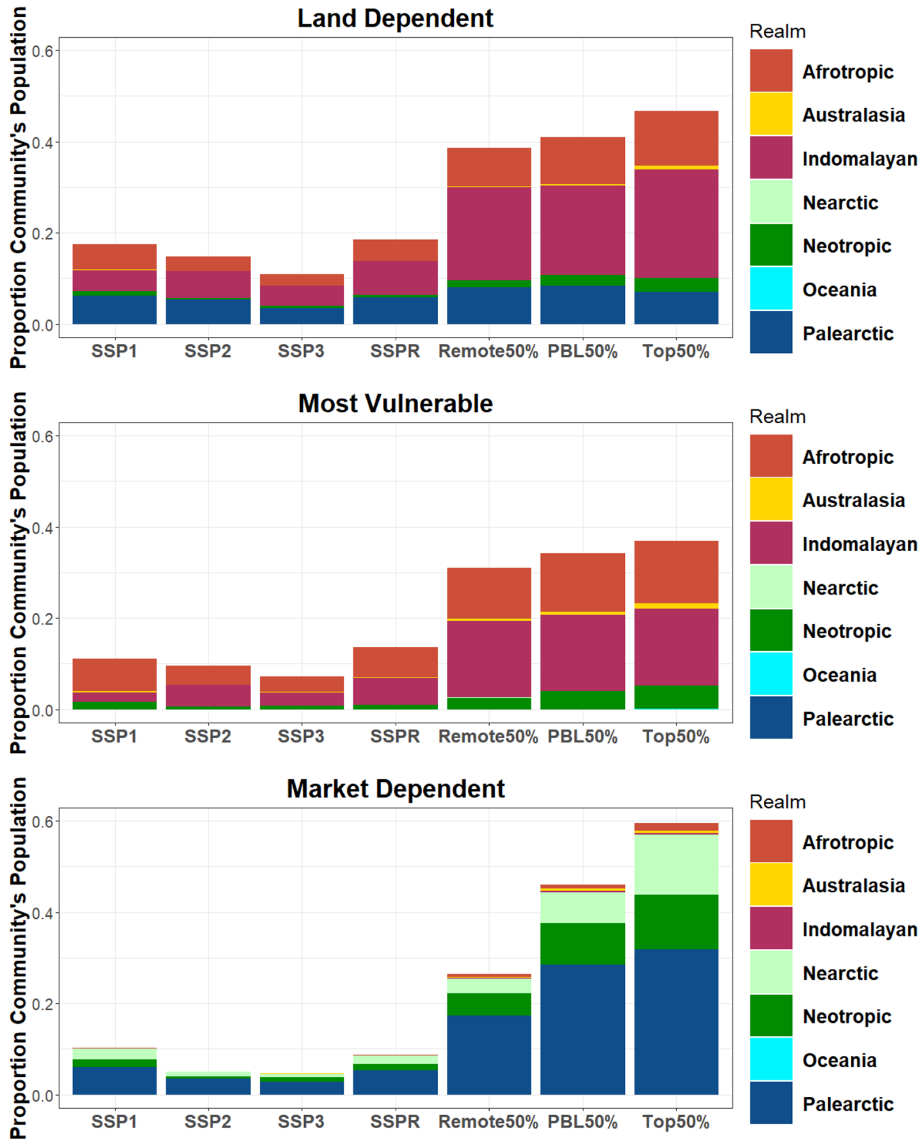

Fig. 4. Relative number of people in Land-Dependent and Most Vulnerable areas compared to Market-Dependent Community areas who would potentially be affected by nature expansion. Values are calculated as the number of people potentially affected in each group, divided by the total population of each globally.

protection scenario could, for example, affect over 1 billion people (52), and result in a loss of 12 to 31% of global cropland and 11 to 29% of global calories (47, 76). Fewer studies have explored how these costs would be distributed across socioeconomic gradients. Here, it has been found that there could be significant risk placed on food production in countries already suffering from

Table 1. Comparative impact of nature expansion on LandDC and MarketDC under a variety of scenarios and conservation prioritizations

	People (%)		Land (%)		Calories ($*10^{12}$)	
	LandDC	MarketDC	LandDC	MarketDC	LandDC	Area nature expansion (km^2)
SSP1	14 (12)	8	16 (15)	17	297	−1,342,700
SSP2	12 (10)	4	11 (10)	10	267	−660,000
SSP3	9 (7)	4	9 (8)	8	238	−4,459,800
SSPR	15 (14)	7	15 (15)	15	342	6,123,600
Remote50%	31 (29)	21	28 (27)	31	667	7,676,500
PBL50%	32 (33)	37	31 (32)	36	632	28,662,100
Top50%	37 (34)	47	33 (32)	38	851	11,847,600

The Most Vulnerable communities are also shown in brackets next to the LandDC values. The proportion of people is calculated as the number of people on either LandDC or MarketDC lands that are affected divided by the total global LandDC or MarketDC population. The proportion of land is calculated as the area of LandDC or MarketDC land affected divided by the total global LandDC or MarketDC land area. The calories described are the amount of food crop calories currently produced which could be put at risk. The final column describes the absolute change in the area of global nature.

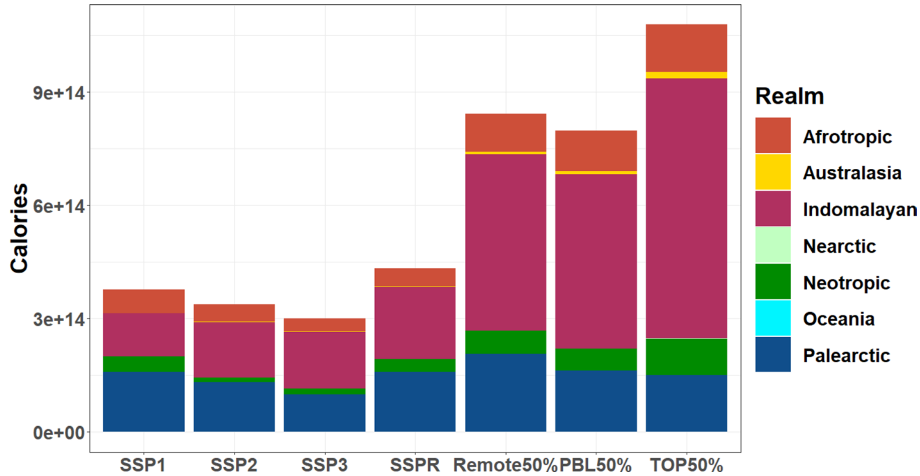

Fig. 5. The yearly calories produced in areas where Land-Dependent Communities are the dominant decision-making type, which are also identified as areas of projected or recommended nature expansion for each of the scenarios and prioritizations, respectively.

undernourishment (76), and the projected increase in food scarcity and cost could increase underweight-related mortality, particularly in developing countries that are not buffered by a strong GDP (53). Additionally, a recent study contrasted a restoration prioritization against population and human development index distributions (14). We build on these studies by demonstrating how the disaggregation of social indicators and inclusion of an explicit equity metric can help evaluate model outputs for their alignment with global normative objectives. Specifically, we identify areas of potential tension between global environmental agendas and nutritional security for LandDCs if conservation is implemented in an exclusive manner. These are critical considerations, as smallholders produce between 30% and 34% of the world's food with low rates of postharvest loss (77), largely in developing countries where they contribute directly to livelihood and nutritional needs (78). The assumption that communities engaged in local small-scale agriculture who need to limit their activities for conservation or restoration purposes will be supported by productivity increases in commercial systems may be misguided. Despite the utility of our framework, LandDCs and MarketDCs often coexist (and can be diverse in themselves) (63), and therefore, other ways of constructing equity as a metric should be explored. For instance, future research could aim to identify equity risks associated with potential social outcomes of various conservation models in terms of access to decision-making power or financial resources across a similar axis of land-use needs or socioeconomic status. As is often the case, finding appropriate data that adequately describe these relationships in sufficient spatial and thematic detail remains a challenge.

To address the tradeoffs between livelihoods and conservation, there has been much debate about alternative conservation strategies that go beyond setting land apart for nature. Such land-sharing strategies describe mixed crop and natural systems in a mosaic of biodiverse cultural landscapes (6, 58, 79, 80) or allow some sustainable use of natural resources by local communities (6, 18, 38). This can provide multiple benefits to local communities through crop diversification and the maintenance of important ecosystem services, while simultaneously improving the ecological connectivity of the landscape (58, 80). Empowering LandDCs to manage their lands for biodiversity is therefore an important strategy for transitioning to sustainability in an equitable manner, ensuring socioeconomic and nutritional security in a changing climate while also reducing the opportunity costs to conservation (6, 34, 58, 81, 82). However, certain vulnerable habitats and the last remaining wilderness areas might only retain their extraordinary values with more strict protection schemes (83–86). Strict protection and social conservation therefore represent diverse tools at opposite ends of a spectrum, and each is suitable in different local contexts.

Our choice of metrics means that we only addressed distributional equity at a very large scale. An important distinction must here be made between equity and justice. If LandDCs pay a smaller share, but conservation and restoration is everywhere practiced in an exclusive manner, then the result will be equitable at the global scale, yet also unjust. Due to the uncertainty surrounding the process by which each future pathway would be implemented, we were only able to identify regions of potential tension, rather than outcomes themselves. Nevertheless, this framework provides a useful tool for exposing assumptions and blind spots in spatial modeling applications for global conservation planning. Moreover, there is a considerable degree of uncertainty associated the with combination of different data and model outputs, which each contain their own sets of assumptions and limitations. Compounding these uncertainties is our use of the land-use decision-making categories as static identities, ignoring the spatial and temporal dynamics of changing socioeconomic status, urbanization, or intergenerational lifestyle changes (87). However, as our intention is to explore where contemporary conservation policies would negatively affect existing vulnerable communities, considering identities as static is in line with our research goals. Another limitation is that while we do engage with normative values of equity and environmental justice, we were not able to consider the diversity of historical circumstances that may have led to or prevented dependence on land systems, such as poverty traps or past displacement (88, 89). Another limitation is related to the calculation of calories which could be put at risk in LandDC areas, in particular, that we were not able to identify potential responses of different food systems to conservation. Coupling our results with economic models, for example, general equilibrium models (with feedbacks to land use models) used to develop some of the existing global scenarios could be one way to address this limitation, even though these have problems in representing the dependence on local land resources. Furthermore, the data used here describe crop allocation to food but not livestock (90). We also did not account for population growth or improvements in LandDC's access to markets. Finally, we focused on a limited set

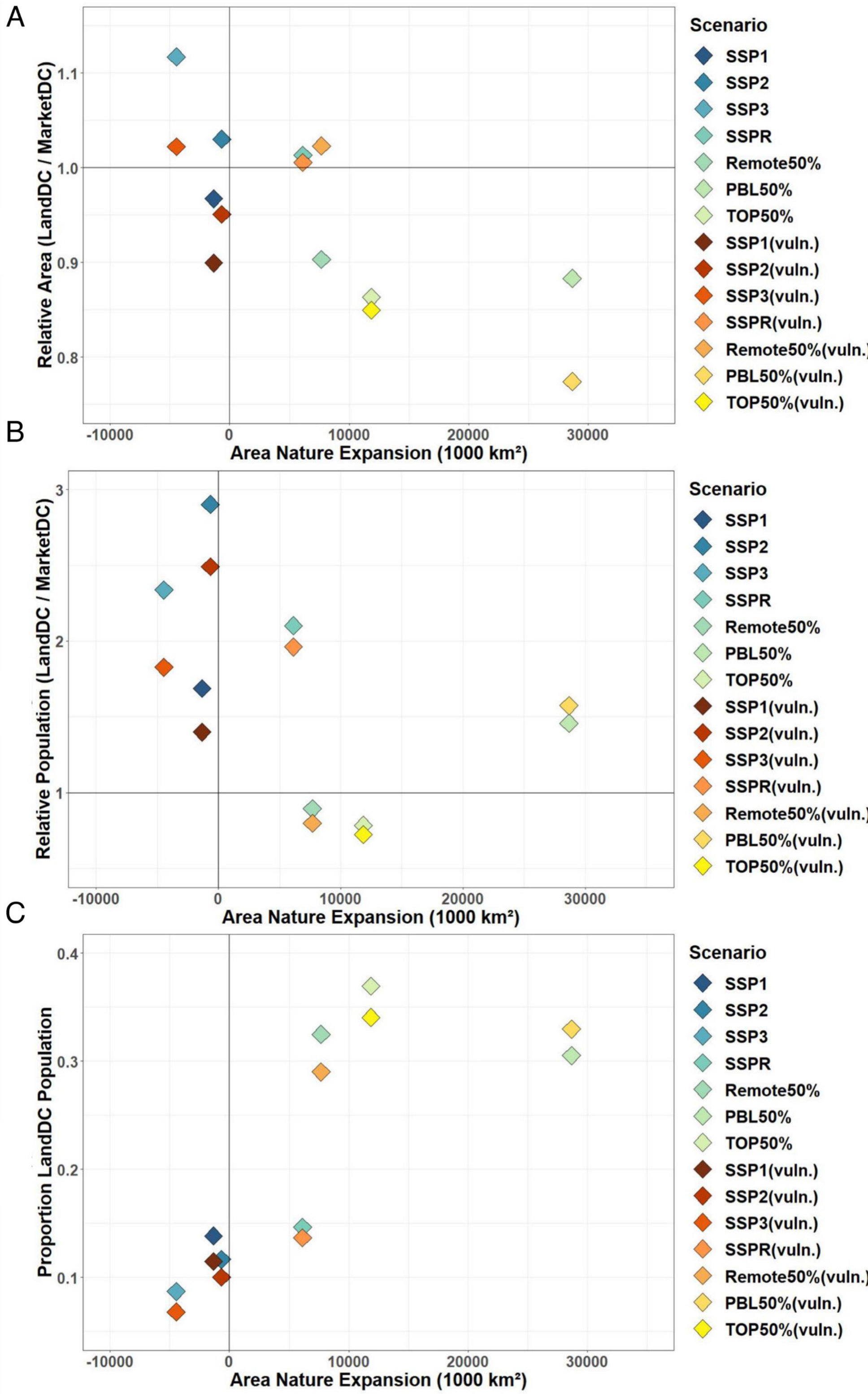

Fig. 6. (*A*) Relationship between nature expansion and equity of outcome in terms of area. The ratio between the relative area of nature expansion into LandDC or most vulnerable (vuln.) areas and MarketDC as a proportion of the total area of land inhabited by each land-user group, plotted against the change in extent of nature. (*B*) Relationship between nature expansion and equity of outcome in terms of population. The ratio between the relative number of people in Land-Dependent or Most Vulnerable areas and Market-Dependent communities as a proportion of the global land-user group population, plotted against the change in extent of nature. (*C*) Relationship between the relative number of people in LandDCs affected and the area of nature expansion. The relative number of Land-Dependent or Most Vulnerable communities, calculated as a proportion of the total global land-dependent population, are plotted against the change in natural extent each of the scenarios and prioritizations.

of scenarios and prioritizations. While these maps allowed for an informative exploration, they provide only a limited view of how land use is likely to change in the future.

The notion of equity in conservation has received considerable attention in local studies; however, our results indicate that such considerations are often lacking in global prioritization and scenario studies. Filling this gap will require a greater inclusion of differentiated social costs and values into integrated assessment and prioritization models, as well as an explicit normative stance on burden sharing. Here, we present one approach for evaluating and comparing potential solutions in terms of their equity, demonstrating the ability—and indeed necessity—for addressing such complex issues in modeling frameworks at large scales. We encourage greater dialogue between conservation and development planners in order to better navigate these trade-offs and to generate solutions that are both spatially optimal and socially just.

Materials and Methods

We evaluated the potential risk of inequity associated with leading scenarios and conservation prioritizations by identifying and comparing areas of potential nature expansion onto LandDC and MarketDC lands (see *SI Appendix*, Appendix A for a list of data sources) (Fig. 1). We highlighted potential hotspots of nature expansion onto LandDC lands (Fig. 2) and calculated the food calories that could be jeopardized if strict exclusionary conservation practices were put in place (Fig. 5). We used R software (91) for data processing, statistical tests, and the creation of plots, and we used QGIS (92) for partitioning data into regions, obtaining population and calorie counts, and creating maps.

We first prepared data on the distribution of land users using the global spatial distribution of Land-use Decision-Making (63), which describes the societal objectives most likely determining localized patterns of land-use change. This dataset was developed by associating the attitudes and objectives of land users as described by 758 different case studies with socioeconomic, climatic, and soil-related variables, which were then used to predict the distribution of six different typologies globally (63). In our study, "LandDC lands" included "Survivalist," "Subsistence-Oriented Smallholder," and "Market-Oriented Smallholder" decision-making types, which are all driven by survival and livelihood objectives. "MarketDC" lands, on the other hand, were associated with "Professional Commercialist," "Professional Intensifier," and "Eco-Agriculturist" decision-making types, which predominantly pursue economic objectives or are otherwise supported by markets. The Market-Oriented Smallholder–which has both survival and economic objectives–was included in the LandDC group as this decision-making type is characterized by their small farm size and often more insecure tenure (63), which would make them more vulnerable following displacement. Excluding this type would have significantly altered the LandDC distribution (*SI Appendix*, Table S1 and Fig. S4). Results were therefore also evaluated for a complementary class which included only the Survivalist and Subsistence-Oriented Smallholders, here called the "Most Vulnerable." These three classes were defined using the categorical map, which shows which decision-making typology is dominant for a given pixel. Using the categorical map also enabled us to better evaluate major geographic trends by comparing the differential impact based on local socioeconomic characteristics. The alternative of thresholding the probability maps was not suitable due to large differences in probability values between regions (meaning that in some areas, lower probabilities indicate the dominant decision-making type compared to another region). In some areas, several types could have low probabilities, leading to potential exclusion of such areas that could simply be a result due to the extrapolation of the regression models used to map the decision-making types in the data. In addition, using probability maps could increase the uncertainty of the decision-making and scenario/prioritization overlay, especially as many areas with low probabilities were also areas of low representativeness for that class. For our analysis, the native resolution of 100 km^2 was maintained, apart from when integrating these data with gridded population counts (93) in order to map decision-making populations at the global scale–information which is otherwise unavailable.

The scenarios considered in the study were the shared socioeconomic pathways SSP1 (the "Sustainability" pathway), the SSP2 (the "Middle of the Road" pathway), and SSP3 (the "Regional Rivalry" pathway) (66, 68). The additional Restoration and Protection Scenario (67) depicts a future where all conservation and restoration targets in international agreements are met. We also included three Half-Earth prioritizations. The Remote50% was developed for this research based on the knowledge that it is often the most remote lands that are conserved first (47, 69, 70). We first identified areas within each ecoregion (15, 94) which are already protected according to the World Database on Protected Areas (95) and then added pixels starting with locations that had the lowest human footprint (96, 97) until 50% of each ecoregion was protected, using R (91). The PBL50% prioritization was developed as a normative "integrated sustainability" scenario for the Netherlands Environmental Assessment Agency (PBL) (71, 72). This was achieved using the IMAGE integrated assessment framework with the GLOBIO biodiversity model to maximize indicators for functional species diversity, minimize and mitigate emissions from land use, and meet global food demands through agricultural intensification, a reduction in food waste, and reduction in demand for animal products (72). Since this scenario included a 2050 timestep in which at least 50% of the Earth's terrestrial and freshwater surface was protected, we used this as a conservation prioritization for our analysis. The final prioritization represented the top 50% of priority regions for climate change mitigation, biodiversity, and freshwater (57) and is therefore defined as the Top50% prioritization.

The distribution of land systems, describing the combinations of land use, land cover, intensity, and livestock presence for the year 2000 (66), was used as a baseline in order to evaluate the change in natural areas for each of the scenarios. "Natural areas" were defined as land systems that did not have any human influence (*SI Appendix*, Appendix B). Through spatial overlay, regions where natural areas expand beyond the baseline distribution into LandDC and MarketDC lands were identified. For the conservation prioritizations, rather than contrasting the distribution of natural areas between the year 2000 and 2050, the prioritizations contrasted natural areas in the year 2000 with protected areas in 2050. For simplicity, this is still referred to as "nature expansion" as they highlight areas in need of restoration.

We then calculated the relative area of expansion onto each of the land users' territories as a proportion of the total area inhabited by each land-user type (Fig. 3). This was done at a global scale as well as per geographic realm (15, 94). Due to the distinct global distribution of land users (as a result of using the categorical map) and how equity is defined in our framework (the ratio between LandDC/MarketDC opportunity costs), large units of analysis such as globally or by geographic realm represent the most suitable scale for evaluating results. Hotspot regions of potential tension were identified by layering the results for each of the scenarios and prioritizations in a bivariate map to show the frequency with which a location is highlighted (Fig. 1). Regions where nature expanded into LandDC and MarketDC lands were then used to identify the number of people living in those areas, using recent spatially explicit data on population density (93). We then also compared the relative number of land users affected as a proportion of the global subpopulation for each decision-making type (Fig. 2). A chi-squared test demonstrated the significance of the association between land-user type and conservation impact by comparing the observed proportions of LandDC and MarketDC land users to the frequencies that would be expected if land dependence had no influence on being affected by nature expansion.

Finally, regions of nature expansion into LandDC lands were also used as a mask to extract data on the crop allocation to food in calories (90, 98). These results were then compared globally and regionally for each scenario and prioritization in order to explore the respective implications for food security (Fig. 5). For our calculations to translate the calories at risk to the number of people that would be affected, we used the humanitarian guidelines of 2,100 calories/person/day (73).

Data, Materials, and Software Availability. Previously published data were used for this work (57, 63, 66, 67, 71, 72, 90, 93–97).

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1. H. Locke, "Nature needs (at least) half: A necessary new agenda for protected areas" in *Protecting the Wild*, G. Wuerthner, E. Crist, T. Butler, Eds. (Island Press/Center for Resource Economics, 2015), pp. 3–15.
2. E. Dinerstein *et al.*, A global deal for nature: Guiding principles, milestones, and targets. *Sci. Adv.* **5**, eaaw2869 (2019).
3. IPBES, "Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services" *Zenodo* (2019). https://doi.org/10.5281/ZENODO.3831674. Accessed 31 August 2021.
4. L. Atwoli *et al.*, Call for emergency action to limit global temperature increases, restore biodiversity and protect health: Wealthy nations must do much more, much faster. *Allergy* **77**, 730–733 (2022).
5. E. Dinerstein *et al.*, A "Global Safety Net" to reverse biodiversity loss and stabilize Earth's climate. *Sci. Adv.* **6**, eabb2824 (2020).
6. N. Dudley *et al.*, The essential role of other effective area-based conservation measures in achieving big bold conservation targets. *Glob. Ecol. Conserv.* **15**, e00424 (2018).
7. B. B. N. Strassburg *et al.*, Global priority areas for ecosystem restoration. *Nature* **586**, 724–729 (2020).
8. B. Mappin *et al.*, Restoration priorities to achieve the global protected area target. *Conserv. Lett.* **12**, e12646 (2019).
9. C. Fastré, W.-J. van Zeist, J. E. M. Watson, P. Visconti, Integrated spatial planning for biodiversity conservation and food production. *One Earth* **4**, 1635–1644 (2021).
10. B. B. N. Strassburg *et al.*, Strategic approaches to restoring ecosystems can triple conservation gains and halve costs. *Nat. Ecol. Evol.* **3**, 62–70 (2019).
11. Convention on Biological Diversity, Update of the zero draft of the post-2020 global biodiversity framework (Convention on Biological Diversity, 2020).
12. C. Sandbrook, J. A. Fisher, G. Holmes, R. Luque-Lora, A. Keane, The global conservation movement is diverse but not divided. *Nat. Sustain.* **2**, 316–323 (2019).
13. IPCC Core Writing Team, "Summary for Policymakers" in *Climate Change 2023: Synthesis Report, Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, H. Lee, J. Romero, Eds. (IPCC, Geneva, Switzerland, 2023), pp. 1–34.
14. S. Löfqvist *et al.*, How social considerations improve the equity and effectiveness of ecosystem restoration. *BioScience* **73**, 134–148 (2022).
15. E. Dinerstein *et al.*, An ecoregion-based approach to protecting half the terrestrial realm. *BioScience* **67**, 534–545 (2017).
16. N. Myers, R. A. Mittermeier, C. G. Mittermeier, G. A. B. da Fonseca, J. Kent, Biodiversity hotspots for conservation priorities. *Nature* **403**, 853–858 (2000).
17. T. M. Brooks *et al.*, Global biodiversity conservation priorities. *Science* **313**, 58–61 (2006).
18. W. M. Adams, J. Hutton, People, parks and poverty: Political ecology and biodiversity conservation. *Conserv. Soc.* **5**, 147–183 (2007).
19. D. O. Obura *et al.*, Integrate biodiversity targets from local to global levels. *Science* **373**, 746–748 (2021).
20. C. Wyborn, M. C. Evans, Conservation needs to break free from global priority mapping. *Nat. Ecol. Evol.* **5**, 1322–1324 (2021), 10.1038/s41559-021-01540-x.
21. R. Yang *et al.*, Cost-effective priorities for the expansion of global terrestrial protected areas: Setting post-2020 global and national targets. *Sci. Adv.* **6**, eabc3436 (2020).
22. B. Schultz *et al.*, Recognizing the equity implications of restoration priority maps. *Environ. Res. Lett.* **17**, 114019 (2022).
23. G. Holmes, Protection, politics and protest: Understanding resistance to conservation. *Conserv. Soc.* **5**, 184–201 (2007).
24. S. M. Redpath *et al.*, Understanding and managing conservation conflicts. *Trends Ecol. Evol.* **28**, 100–109 (2013).
25. S. R. Brechin, P. R. Wilshusen, C. L. Fortwangler, P. C. West, Beyond the square wheel: Toward a more comprehensive understanding of biodiversity conservation as social and political process. *Soc. Nat. Resour.* **15**, 41–64 (2002).
26. A. Martin, A. Akol, N. Gross-Camp, Towards an explicit justice framing of the social impacts of conservation. *Conserv. Soc.* **13**, 166–178 (2015).
27. S. Lele, P. Wilshusen, D. Brockington, R. Seidler, K. Bawa, Beyond exclusion: Alternative approaches to biodiversity conservation in the developing tropics. *Curr. Opin. Environ. Sustain.* **2**, 94–100 (2010).
28. T. R. Miller, B. A. Minteer, L.-C. Malan, The new conservation debate: The view from practical ethics. *Biol. Conserv.* **144**, 948–957 (2011).
29. G. Fedele, C. I. Donatti, I. Bornacelly, D. G. Hole, Nature-dependent people: Mapping human direct use of nature for basic needs across the tropics. *Glob. Environ. Change* **71**, 102368 (2021).
30. E. Beauchamp, T. Clements, E. J. Milner-Gulland, Exploring trade-offs between development and conservation outcomes in Northern Cambodia. *Land Use Policy* **71**, 431–444 (2018).
31. N. Dawson, B. Coolsaet, A. Martin, "Justice and equity: Emerging research and policy approaches to address ecosystem service trade-offs" in *Ecosystem Services and Poverty Alleviation Trade-Offs and Governance* (Routledge, 2018), pp. 22–38.
32. V. Tauli-Corpuz, J. Alcorn, A. Molnar, C. Healy, E. Barrow, Cornered by PAs: Adopting rights-based approaches to enable cost-effective conservation and climate action. *World Dev.* **130**, 104923 (2020).
33. T. C. Sunderland, W. Vasquez, Forest conservation, rights, and diets: Untangling the issues. *Front. For. Glob. Change* **3**, 29 (2020).
34. B. Büscher, R. Fletcher, Towards convivial conservation. *JSTORE* **17**, 283–296 (2019).
35. P. Kashwan, R. V. Duffy, F. Massé, A. P. Asiyanbi, E. Marijnen, From racialized neocolonial global conservation to an inclusive and regenerative conservation. *Environ. Sci. Policy Sustain. Dev.* **63**, 4–19 (2021).
36. S. L. Maxwell *et al.*, Area-based conservation in the twenty-first century. *Nature* **586**, 217–227 (2020).
37. J. S. Sze, L. R. Carrasco, D. Childs, D. P. Edwards, Reduced deforestation and degradation in Indigenous Lands pan-tropically. *Nat. Sustain.* **5**, 123–130 (2022).
38. W. M. Adams *et al.*, Biodiversity conservation and the eradication of poverty. *Science* **306**, 1146–1149 (2004).
39. S. Hoffmann, Advances in conservation biogeography: Towards protected area effectiveness under anthropogenic threats. *Front. Biogeogr.* **13**, 1–23 (2021).
40. A. Martin, S. McGuire, S. Sullivan, Global environmental justice and biodiversity conservation: Global environmental justice and biodiversity conservation. *Geogr. J.* **179**, 122–131 (2013).
41. C. Corson, I. Flores-Ganley, J. Worcester, S. Rogers, From paper to practice? Assembling a rights-based conservation approach *J. Polit. Ecol.* **27**, 1128–1147 (2020).
42. D. Armitage, P. Mbatha, E. Muhl, W. Rice, M. Sowman, Governance principles for community-centered conservation in the post-2020 global biodiversity framework. *Conserv. Sci. Pract.* **2**, e160 (2020).
43. A. Agrawal, K. Redford, Conservation and displacement: An overview. *Conserv. Soc.* **7**, 1–10 (2009).
44. E. Lunstrum, M. Ybarra, Deploying difference: Security threat narratives and state displacement from protected areas. *Conserv. Soc.* **16**, 114–124 (2018).
45. T. Kepe, "Meanings, alliances and the state in tensions over land rights and conservation in South Africa" in *Land Rights, Biodiversity Conservation and Justice* (Routledge, 2018).
46. S. Boillat *et al.*, Distant interactions, power, and environmental justice in protected area governance: A telecoupling perspective. *Sustainability* **10**, 3954 (2018).
47. E. C. Ellis, Z. Mehrabi, Half Earth: Promises, pitfalls, and prospects of dedicating Half of Earth's land to conservation. *Curr. Opin. Environ. Sustain.* **38**, 22–30 (2019).
48. T. O. McShane *et al.*, Hard choices: Making trade-offs between biodiversity conservation and human well-being. *Biol. Conserv.* **144**, 966–972 (2011).
49. E. O. Wilson, *Half-Earth: Our Planet's Fight for Life* (WW Norton & Company, 2016), 7 May 2022.
50. H. Locke, Nature needs half: A necessary and hopeful new agenda for protected areas. *PARKS* **19**, 13–22 (2013).
51. E. C. Ellis, To conserve nature in the Anthropocene, half earth is not nearly enough. *One Earth* **1**, 163–167 (2019).
52. J. Schleicher *et al.*, Protecting half of the planet could directly affect over one billion people. *Nat. Sustain.* **2**, 1094–1096 (2019).
53. R. C. Henry *et al.*, Global and regional health and food security in a Half Earth world. *Nat. Sustain.* **5**, 1–8 (2022).
54. N. C. Ban *et al.*, A social–ecological approach to conservation planning: Embedding social considerations. *Front. Ecol. Environ.* **11**, 194–202 (2013).
55. F. Montesino Pouzols *et al.*, Global protected area expansion is compromised by projected land-use and parochialism. *Nature* **516**, 383–386 (2014).
56. R. Chaplin-Kramer *et al.*, Mapping the planet's critical natural assets. *Nat. Ecol. Evol.* **7**, 51–61 (2022).
57. M. Jung *et al.*, Areas of global importance for conserving terrestrial biodiversity, carbon and water. *Nat. Ecol. Evol.* **5**, 1499–1509 (2021), 10.1038/s41559-021-01528-7.
58. S. Wolff, J. Meijer, C. J. E. Schulp, P. H. Verburg, Contextualizing local landscape initiatives in global change: A scenario study for the high forest zone, Ghana. *Reg. Environ. Change* **20**, 115 (2020).
59. K. Moon, N. K. Browne, Developing shared qualitative models for complex systems. *Conserv. Biol.* **35**, 1039–1050 (2021).
60. P. Mazzega, On the ethics of biodiversity models, forecasts and scenarios. *Asian Bioeth. Rev.* **10**, 295–312 (2018).
61. D. Leclère *et al.*, Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* **585**, 551–556 (2020).
62. J. Leventon, J. Laudan, Local food sovereignty for global food security? Highlighting interplay challenges. *Geoforum* **85**, 23–26 (2017).
63. Ž Malek, P. H. Verburg, Mapping global patterns of land use decision-making. *Glob. Environ. Change* **65**, 102170 (2020).
64. E. H. Nyekwere, N. C. Ole, Understanding the principle of common but differentiated responsibilities and its manifestations in multilateral environmental agreements (MEAS). *Nnamdi Azikiwe Univ. Awka J. Public Priv. Law* **11**, 262–284 (2021).
65. E. Stehfest *et al.*, Key determinants of global land-use projections. *Nat. Commun.* **10**, 2166 (2019).
66. B. Schrammeijer, P. Verburg, Implementing SSPs in CLUMondo (2019). https://doi.org/10.34894/4VLMP7. Accessed 12 July 2021.
67. S. Wolff, E. A. Schrammeijer, C. J. E. Schulp, P. H. Verburg, Meeting global land restoration and protection targets: What would the world look like in 2050? *Glob. Environ. Change* **52**, 259–272 (2018).
68. B. C. O'Neill *et al.*, The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change* **42**, 169–180 (2017).
69. O. Venter *et al.*, Targeting global protected area expansion for imperiled biodiversity. *PLoS Biol.* **12**, e1001891 (2014).
70. O. Venter *et al.*, Bias in protected-area location and its effects on long-term aspirations of biodiversity conventions: Protected Areas Missing Biodiversity. *Conserv. Biol.* **32**, 127–134 (2018).
71. M. Immovilli, M. Kok, "Narratives for the 'half earth' and 'sharing the planet' scenarios: A literature review" (PBL publication number: 4226, PBL Netherlands Environmental Assessment Agency, The Hague, 2020).
72. M. T. J. Kok *et al.*, Assessing ambitious nature conservation strategies within a 2 degree warmer and food-secure world. bioRxiv [Preprint] (2020). https://doi.org/10.1101/2020.08.04.236489 (30 November 2021).
73. The Sphere Project, "Minimum standards in food security and nutriontion" in *Humanitarian Charter and Minimum Standards in Humanitarian Response* (JSTORE, 2011), pp. 138–238.
74. L. Swamy, E. Drazen, W. R. Johnson, J. J. Bukoski, The future of tropical forests under the United Nations Sustainable Development Goals. *J. Sustain. For.* **37**, 221–256 (2018).
75. S. K. Jones, A. Monjeau, K. Perez-Guzman, P. A. Harrison, Integrated modeling to achieve global goals: Lessons from the Food, Agriculture, Biodiversity, Land-use, and Energy (FABLE) initiative. *Sustain. Sci.* **18**, 323–333 (2023), 10.1007/s11625-023-01290-8.
76. Z. Mehrabi, E. C. Ellis, N. Ramankutty, The challenge of feeding the world while conserving half the planet. *Nat. Sustain.* **1**, 409–412 (2018).
77. V. Ricciardi, N. Ramankutty, Z. Mehrabi, L. Jarvis, B. Chookolingo, How much of the world's food do smallholders produce? *Glob. Food Secur.* **17**, 64–72 (2018).
78. T. Tscharntke *et al.*, Global food security, biodiversity conservation and the future of agricultural intensification. *Biol. Conserv.* **151**, 53–59 (2012).
79. A. C. de la Vega-Leinert, P. Clausing, Extractive conservation. *Environ. Soc.* **7**, 50–70 (2016).
80. I. Grass *et al.*, Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation. *People Nat.* **1**, 262–272 (2019).
81. J. M. H. Green *et al.*, Local costs of conservation exceed those borne by the global majority. *Glob. Ecol. Conserv.* **14**, e00385 (2018).
82. United Nations General Assembly, Transforming Our World: The 2030 Agenda for Sustainable Development (United Nations, 2015).
83. J. E. M. Watson *et al.*, Protect the last of the wild. *Nature* **563**, 27–30 (2018).

84. M. Di Marco, S. Ferrier, T. D. Harwood, A. J. Hoskins, J. E. M. Watson, Wilderness areas halve the extinction risk of terrestrial biodiversity. *Nature* **573**, 582–585 (2019).
85. J. E. M. Watson *et al.*, Set a global target for ecosystems. *Nature* **578**, 360–362 (2020).
86. M. G. Betts *et al.*, Global forest loss disproportionately erodes biodiversity in intact landscapes. *Nature* **547**, 441–444 (2017).
87. Ž. Malek, B. Douw, J. Van Vliet, E. H. Van Der Zanden, P. H. Verburg, Local land-use decision-making in a global context. *Environ. Res. Lett.* **14**, 083006 (2019).
88. S. Batterbury, Landscapes of diversity: A local political ecology of livelihood diversification in south-western Niger. *Ecumene* **8**, 437–464 (2001).
89. B. King, Spatialising livelihoods: Resource access and livelihood spaces in South Africa. *Trans. Inst. Br. Geogr.* **36**, 297–313 (2011).
90. E. S. Cassidy, P. C. West, J. S. Gerber, J. A. Foley, Redefining agricultural yields: from tonnes to people nourished per hectare. *Environ. Res. Lett.* **8**, 034015 (2013).
91. R Core Team, R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing (Vienna, Austria, 2021). https://www.R-project.org/.
92. QGIS Development Team, QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org. Accessed 1 December 2020.
93. Center For International Earth Science Information Network-CIESIN-Columbia University, Gridded Population of the World, Version 4 (GPWv4): Population Count Adjusted to Match 2015 Revision of UN WPP Country Totals, Revision 11 (2018) https://doi.org/10.7927/H4PN93PB (1 September 2021).
94. E. Dinerstein, *et al.*, An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. *BioScience* **67**, 534–545 (2017).
95. UNEP-WCMC and IUCN, Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM). [WDPA_WDOECM Database]. https://www.protectedplanet.net/en/search-areas?geo_type=site. Accessed 1 September 2021.
96. O. Venter *et al.*, Global terrestrial Human Footprint maps for 1993 and 2009. *Sci. Data* **3**, 160067 (2016).
97. O. Venter *et al.*, Data from: Global terrestrial Human Footprint maps for 1993 and 2009. Dryad. https://doi.org/10.5061/dryad.052q5. Accessed 1 September 2021.
98. E. S. Cassidy, P. C. West, J. S. Gerber, J. A. Foley, Redefining agricultural yields: From tonnes to people nourished per hectare. *Environ. Res. Lett.* **8**, 034015 (2013).