Land-Efficient Allocation of Agricultural Production Under Alternative Trade Regimes: Implications for Global Land-Use Change and Biodiversity

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Abstract

Agricultural expansion is a major driver of global biodiversity loss, yet future food demand is expected to continue increasing. Because land productivity varies widely across regions, the spatial allocation of agricultural production may strongly influence how much land is required to meet that demand. International trade shapes this allocation, but it remains unclear whether alternative trade regimes can reduce land-use pressure and biodiversity loss.

We evaluated how alternative future trade regimes affect global agricultural production, land use, and biodiversity under a baseline, uniform liberalization, uniform protectionism, and a productivity-oriented regime that favors production in relatively land-efficient locations.

Uniform trade liberalization increased trade and production, but also expanded cropland and lowered global crop land productivity, indicating a shift towards less land-efficient production. Protectionism did not provide a clear biodiversity benefit. By contrast, the productivity-oriented regime increased global land productivity, reduced agricultural land demand, and alleviated biodiversity loss.

These results show that the environmental effects of trade depend not simply on trade openness, but on how alternative trade regimes shape the geography of production. Trade frameworks that better align production with land productivity could help reduce the land required to meet future food demand and thereby limit biodiversity loss. More broadly, the findings suggest that international trade regimes may be an important, but underexplored, component of strategies to reconcile food production with biodiversity conservation.

Background

Biodiversity is declining at an unprecedented rate under human pressure, and land-use change associated with agricultural expansion has been identified as its largest direct driver in terrestrial ecosystems[1]. As natural habitats are converted into cropland and pasture, biodiversity loss threatens not only species persistence but also ecosystem functions and services essential to human well-being. At the same time, global food demand is expected to continue increasing due to population growth, economic development, and dietary change[2]. Although past increases in food production were supported by technological progress and yield improvements, recent evidence suggests that yield growth is slowing in many regions, raising concerns that future demand may increasingly be met through agricultural expansion[3].

Under current socioeconomic trends, agricultural land area is projected to continue expanding[4], with potentially severe consequences for ecosystems and biodiversity. However, several studies have suggested that future food demand could be met with less land if production were spatially reallocated toward more productive regions[5,6]. Because agricultural productivity differs substantially across locations, the spatial allocation of production is likely to be a key determinant of future land demand.

International trade plays a central role in shaping the geography of food production and therefore may strongly influence land-use efficiency at the global scale. In principle, trade could reduce pressure on land if it shifts production toward regions with higher land productivity. In practice, however, trade liberalization has often shifted production toward areas with lower land and labor costs rather than higher biophysical productivity, including biodiversity-rich tropical regions[7–9]. As a result, expanding trade can contribute to deforestation, habitat loss, and biodiversity decline far from the locations where food is consumed.

Despite growing recognition of these linkages, it remains unclear how alternative future trade-policy settings may affect the spatial allocation of agricultural production, land-use change, and biodiversity outcomes. In particular, the biodiversity consequences of alternative trade regimes have not been systematically assessed at the global scale[10,11]. To address this gap, this study examines multiple future trade regimes and evaluates how they affect agricultural land-use change and biodiversity impacts. In doing so, we assess whether and how alternative trade regimes could reduce agricultural expansion and mitigate global biodiversity loss.

Methodology

We assessed future agricultural land-use change and its biodiversity impacts by integrating the global agricultural partial equilibrium model AIM-ALPHA[12], the land-use downscaling model AIM-PLUM[13], and the biodiversity model PREDICTS[14] (**Fig. 1**). AIM-ALPHA[12,15] represents agricultural production in 400 subnational river-basin units and food demand in 166 countries, and endogenously determines supply, demand, prices, land allocation, and international trade for 23 agricultural commodities from 2015 to 2100. Within the model, land is allocated among major land-use categories in response to land rents using a nested logit structure, while international trade flows are determined by trade costs and policy variables, including tariff rates and producer support estimates (PSEs). This framework enables consistent simulation of how changes in trade policy alter commodity markets, production incentives, and land-use patterns over time.

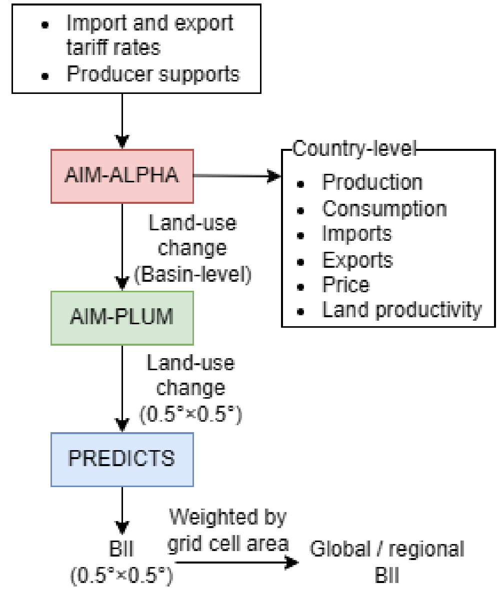

Figure 1. Model framework

The basin-level land-use outputs from AIM-ALPHA were spatially downscaled to a 0.5° × 0.5° gridded resolution using AIM-PLUM[13], a global land-use allocation model designed to translate aggregated land-demand projections into spatially explicit land-use patterns. These gridded land-use projections were then linked to biodiversity outcomes using the PREDICTS[14] framework, which estimates terrestrial biodiversity responses to land use based on empirically derived relationships between land use and local species abundance and community composition. From these relationships, we calculated the Biodiversity Intactness Index (BII), an indicator scaled from 0 to 1 that represents the intactness of biodiversity relative to minimally disturbed conditions, with higher values indicating biodiversity closer to its minimally disturbed state.

To examine the role of alternative trade regimes, we compared four scenarios representing different trade-policy settings: BASE, DECR, INCR, and PROD (**Table 1**). In all scenarios, socioeconomic drivers followed SSP2, and climate change impacts on agricultural productivity were not considered. Trade-related measures were represented by commodity-specific import tariffs, export tariffs, and PSEs, which together influence domestic prices, trade competitiveness, and production incentives. The BASE scenario fixed these variables at 2015 levels; DECR and INCR imposed uniform decreases and increases, respectively. PROD, by contrast, differentiated changes according to whether a country's commodity-specific land productivity (production per hectare for each agricultural commodity) in 2015 was above or below the global average. The combination in PROD was intended to strengthen domestic production incentives and export competitiveness in relatively land-efficient countries, while weakening them in less land-efficient countries, in order to test whether production could be reallocated toward higher land-productivity locations.

Table 1. Summary of trade-policy scenarios.

Scenario	Trade-policy setting	Import tariff	Export tariff	PSE
BASE	2015 policy setting fixed throughout the simulation period.	Fixed at 2015 levels (2015–2100).		
DECR	Uniform trade liberalization.	Reduced by 50% by 2050, then held constant		
INCR	Uniform protectionism.	Increased by 50% by 2050, then held constant		
PROD	Productivity-oriented regime based on whether 2015 commodity-specific land productivity is above or below the global average.	High-productivity countries: +50%; low-productivity countries: −50% by 2050, then held constant	High-productivity countries: −50%; low-productivity countries: +50% by 2050, then held constant	High-productivity countries: +50%; low-productivity countries: −50% by 2050, then held constant

Results

Impacts on the food system

Global crop and livestock production increased throughout the century in all scenarios, reflecting rising food demand driven by population growth and economic development, and international trade volumes also increased (**Fig. 2a,b**). The magnitude of these changes, however, varied across trade-policy settings. Relative to BASE, crop trade increased substantially under both DECR and PROD, reaching +1,052 million t and +672 million t in 2100, respectively. Livestock trade also increased under DECR (+51 million t in 2100), whereas it declined under INCR (−69 million t in 2100) (**Fig. 2b**).

These trade-policy shifts were accompanied by changes in the regional distribution of agricultural production (**Fig. 2c**). Under DECR, global production exceeded that in BASE for both crops and livestock, with especially strong increases in OECD & EU and Latin America, while production declined in Asia. INCR showed broadly opposite regional responses to DECR across many regions. Under PROD, global crop production increased relative to BASE, with particularly strong growth in Latin America, whereas production declined in Middle East and Africa.

Consumer prices responded in parallel to these changes in trade conditions (**Fig. 3**). In DECR, global agricultural consumer prices were 3.5% lower than in BASE by 2100, and most regions experienced price declines. In contrast, INCR raised consumer prices in many regions relative to BASE. PROD reduced prices at the global level, but regional responses were mixed: consumer prices increased in Reforming Economies, OECD & EU, and Asia despite the overall global decline.

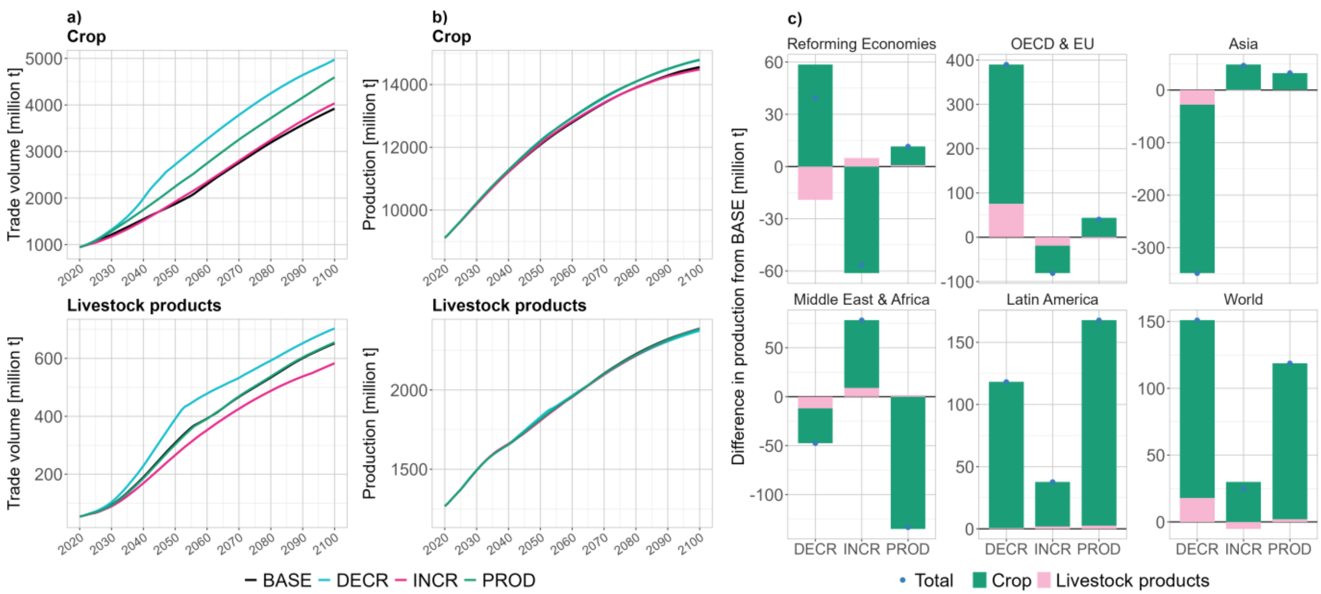

Figure 2. Global production and trade, and regional production responses under alternative scenarios. a) Global crop and livestock production; b) global crop and livestock trade; c) differences in regional agricultural production in 2050 relative to the BASE scenario for the five R5 regions and the world (bars: crop and livestock production; points: total agricultural production).

Figure 3. Regional agricultural consumer price responses relative to the BASE scenario. Bars show percentage differences in agricultural consumer prices in 2100 relative to the BASE scenario for the DECR, INCR and PROD scenarios, across the five R5 regions and the world.

Land-use change

Global land-use trajectories differed markedly across scenarios (**Fig. 4a**). Relative to BASE, DECR led to a substantial expansion of cropland, reaching +49 million ha in 2100. In contrast, INCR reduced cropland area by 22 million ha in 2100 relative to BASE, while increasing pasture area by 77 million ha. PROD produced the most land-efficient outcome among the scenarios: cropland declined by 60 million ha and pasture by 25 million ha relative to BASE in 2100, while forest and other natural land expanded by a combined 83 million ha in 2100. These results suggest that trade conditions designed to favor production in land-efficient locations can reduce overall agricultural land demand and increase the retention of natural land.

These land-use outcomes were closely associated with changes in global average land productivity (**Fig. 4b**). In BASE, both crop and livestock productivity improved gradually over time as a result of technological progress. Under DECR, however, average crop productivity was lower than in BASE, indicating that production shifted toward areas with lower land productivity. By contrast, PROD increased both crop and livestock productivity relative to BASE, consistent with a spatial reallocation of production toward areas with higher land productivity. As a result, less agricultural land was required under PROD to sustain agricultural production.

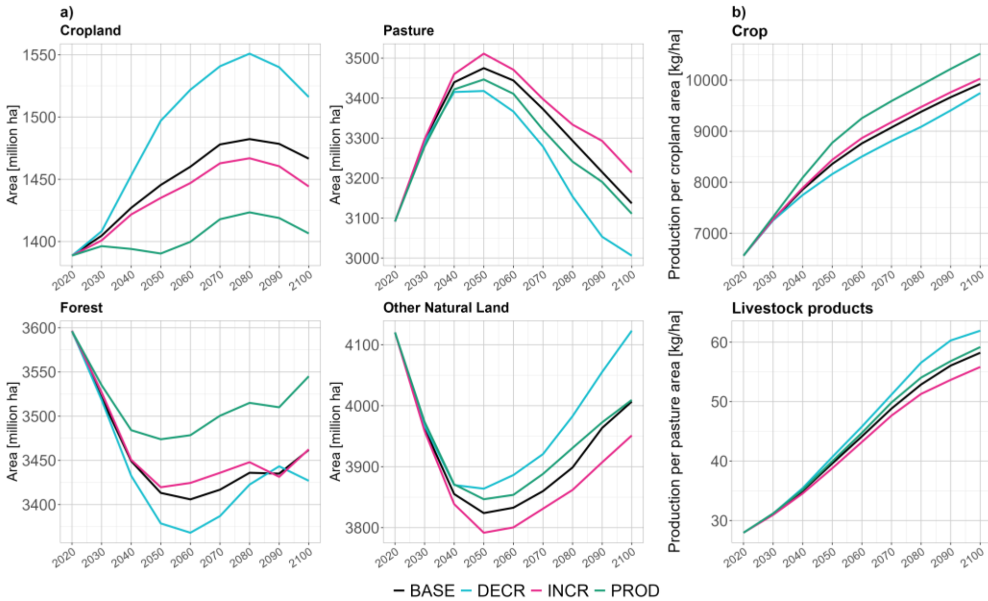

Figure 4. Global land-use and land productivity responses under alternative scenarios. a) Changes in cropland, pasture, forest and other natural land; b) crop and livestock land productivity.

Biodiversity impacts

Global BII declined under the BASE scenario, indicating continued biodiversity loss over time (**Fig. 5**). DECR showed a similar downward trajectory, but with larger declines than BASE in several regions, most notably in OECD & EU and Latin America. INCR also produced a global decline in BII broadly comparable to that in BASE, although the reduction was particularly pronounced in Middle East and Africa.

In contrast, PROD moderated the decline in global BII relative to the other scenarios (**Fig. 5**). By 2100, BII exceeded BASE levels in many regions, suggesting that a productivity-oriented reallocation of agricultural production can alleviate biodiversity loss associated with land-use change. This improvement was also evident in the spatial distribution of BII, with many areas showing higher BII under PROD than under BASE (**Fig. 6**).

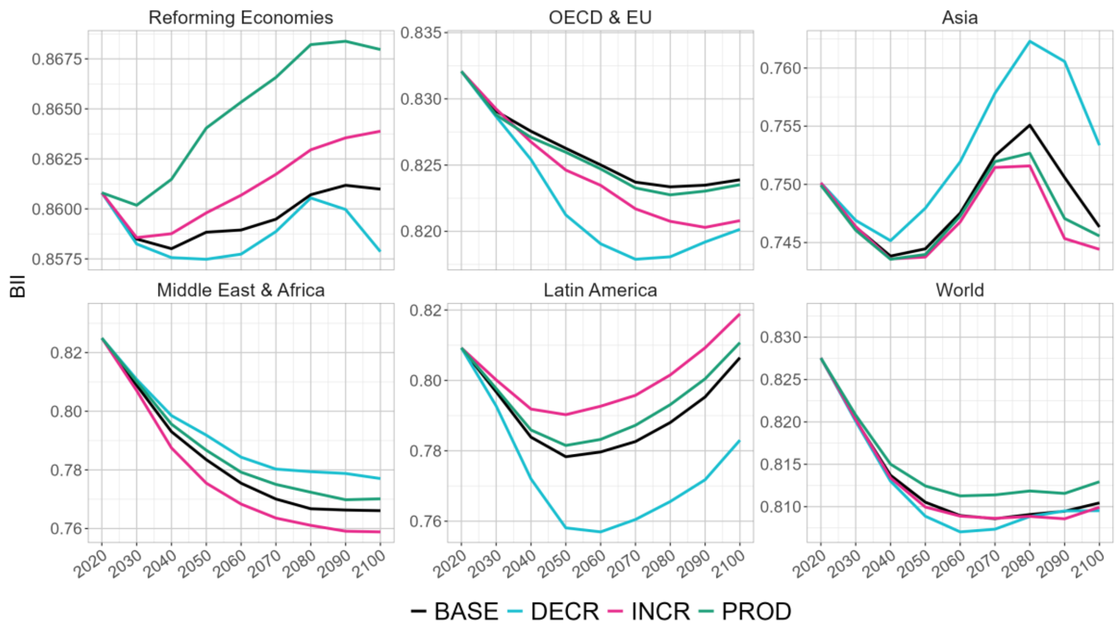

Figure 5. Regional and global biodiversity trajectories under alternative scenarios. Time series of the Biodiversity Intactness Index (BII) for the five R5 regions and the world.

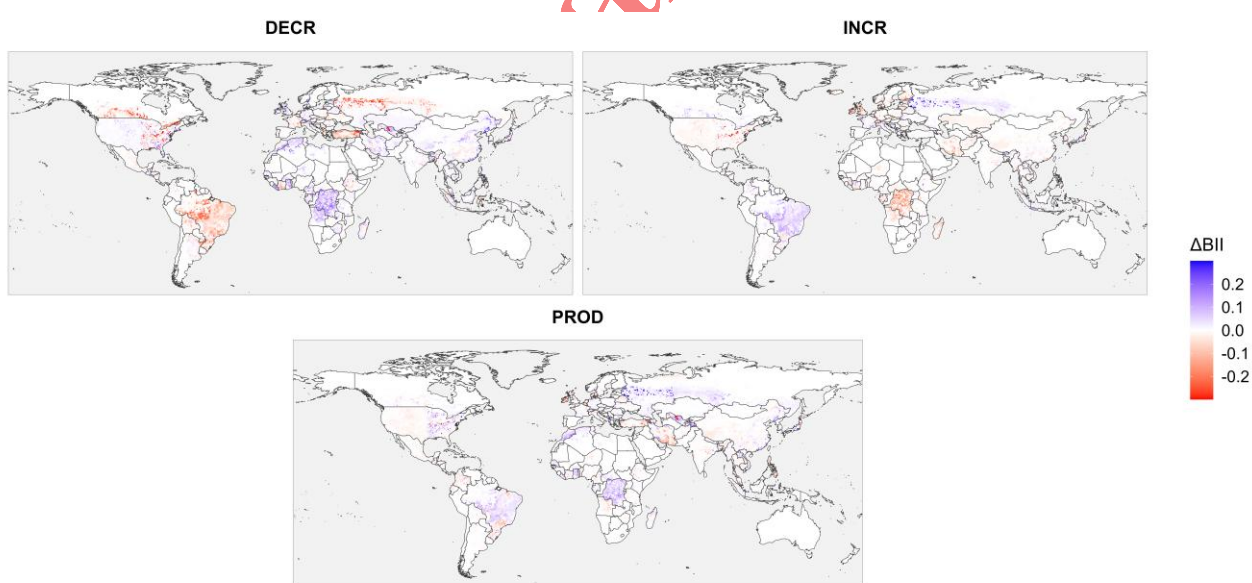

Figure 6. Spatial redistribution of global biodiversity in 2100 under alternative scenarios. Shown are differences in BII from BASE.

Discussion and conclusion

This study shows that alternative trade regimes can substantially influence long-term land-use change and biodiversity outcomes, and that these effects depend not simply on the degree of trade openness, but on how trade regimes are structured. Across the scenarios, changes in tariffs and producer support altered trade flows, the regional distribution of agricultural production, land-use patterns, and biodiversity trajectories. In particular, the results indicate that trade-related conditions affect environmental outcomes by shaping the spatial allocation of agricultural production and, in turn, the land required to meet future food demand.

A key finding is that uniform trade liberalization (DECR) did not necessarily improve land-use efficiency. Although it increased agricultural trade and production (**Fig. 2**), it was also associated with lower global crop land productivity and greater cropland expansion (**Fig. 4**), indicating a shift of production toward locations with lower land productivity. This pattern implies that trade liberalization can intensify pressure on land when production expands in regions where agricultural output requires relatively large areas. In contrast, the protectionist scenario (INCR) did not provide a clear biodiversity benefit either, as lower cropland area was accompanied by pasture expansion in some regions (**Figs. 4 and 5**). Together, these results indicate that neither broad liberalization nor broad protectionism is sufficient, by itself, to reduce land-use pressure and biodiversity loss.

By contrast, the productivity-oriented scenario (PROD) produced the most land-efficient outcome. By favoring production in countries with relatively high land productivity, this scenario increased global average land productivity, reduced agricultural land demand, and alleviated biodiversity loss relative to the other scenarios. This suggests that trade frameworks explicitly aligned with land-use efficiency could complement conventional conservation and agricultural development strategies by reducing the amount of land required to meet future food demand. At the same time, regional production and price responses remained uneven, implying that such a regime could generate distributional consequences across countries and regions and may therefore require accompanying measures to address economic adjustment, food access, and equity concerns.

Several limitations should be noted. First, biodiversity impacts were assessed using a single indicator, the Biodiversity Intactness Index derived from land-use projections, which does not capture all dimensions of biodiversity change. Second, because the analysis is based on a partial equilibrium framework, it does not capture economy-wide adjustment processes such as intersectoral factor reallocation, income-mediated demand changes, or broader welfare effects. Third, this study does not evaluate the broader economic and food-security consequences of alternative trade regimes. Fourth, the productivity-oriented scenario is based on relative productivity in the base year and should be interpreted as a stylized exploratory case rather than a directly implementable policy design; it also does not account for future changes in comparative advantage arising from climate change or other environmental and technological shifts. The scenarios should therefore be interpreted as exploratory rather than predictive.

Overall, our results indicate that the structure of trade regimes matters for both land-use efficiency and biodiversity conservation. Uniform changes in trade barriers and producer support do not necessarily reduce environmental pressure, whereas a trade regime that directs production toward more land-efficient locations has the potential to limit agricultural expansion and mitigate biodiversity loss. These findings provide a basis for considering international trade regimes as one possible component of future strategies to reconcile food production with biodiversity conservation.

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