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Land footprints of the food system reveal telecoupled biodiversity impacts

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THE FOOD SYSTEM DRIVES LAND-USE CHANGES BEYOND WHERE FOOD IS CONSUMED

Land-use changes driven by human activities are widely recognized as a major factor in global biodiversity decline, raising concerns regarding the potential sixth mass extinction. Against the background of globalization and the rising demand for agricultural products, the food system increasingly drives land-use changes beyond regions where food is consumed, primarily through international trade and global supply chains. The global food system spans complex networks that connect agricultural production, distribution, processing, and consumption, intertwining environmental, economic, and social systems beyond national borders. In many cases, countries outsource the environmental costs of domestic food consumption, with agricultural expansion and intensification occurring outside their territories. For example, the United States appropriates large amounts of foreign cropland to meet domestic demand, and accounts for roughly 10% of cropland embodied in global agricultural trade, largely through imports of vegetables, fruits, and nuts.[1] Beyond cropland, meat-rich diets in high-income economies, such as the United States, the European Union, and Japan, also rely heavily on grazing land located in distant regions.

Given this spatial separation between food consumption and production, consumption decisions, such as dietary choices and lifestyles, can influence land-use changes in distant production regions. Critically, such outsourcing is primarily driven by consumption in the Global North, placing pressure on land conversion in the Global South and externalizing a major share of associated land footprints.[1,2] As a result, environmental pressures generated by consumption in one place increasingly result in ecological consequences elsewhere through trade and resource flows (Figure 1A). This pattern highlights the growing prevalence of human-nature interactions across distant systems (i.e., telecoupling), where actions in one part of the world cascade and impact regions far away — a concept that has gained prominence as international trade deepens and environmental concerns become more urgent.[3]

LAND FOOTPRINTS MAKE TELECOUPLED BIODIVERSITY IMPACTS VISIBLE

By attributing land-use changes to final consumption, land footprint accounting reveals telecoupled biodiversity impacts of the food system, which are often obscured in conventional production-based assessments. While importing agricultural products might help maintain domestic habitats, it generally comes at the cost of offshoring biodiversity losses to other regions. From this consumption perspective, economically developed countries tend to cause greater international biodiversity loss than domestic biodiversity loss through outsourced deforestation, with the former being, on average, 15.2 times greater than the latter.[2] These impacts might be further intensified in regions with geographically concentrated production of specific commodities for global markets. For instance, surging vanilla prices have increased the direct land footprint from vanilla cultivation in Madagascar, a major global supplier, while also generating indirect land footprints through the expansion of other crops driven by rising farmer incomes.[2] These cascading impacts raise particular concern for biodiversity hotspots like Madagascar, which harbor large numbers of endemic species. Such apprehensions extend to other vulnerable regions that support high biodiversity and depend economically on certain export commodities, as shifts in consumption patterns and commodity prices can impose disproportionate biodiversity impacts on these areas through global supply chains.

Crucially, the magnitude of these impacts varies drastically across food commodities. This variation can be understood through the lens of biodiversity opportunity cost: agricultural land use driven by global food consumption represents a forgone opportunity for habitat restoration, increasing species extinction risks.[4] Quantifying this concept in global supply chains remains challenging and typically requires integrating species distribution data, high-resolution land-use maps, and multi-region input-output analysis. Within this framework, producing 1 kg of animal products typically results in much higher extinction impacts than producing 1 kg of staple crops, largely due to the dual demand for both grazing land and cropland for livestock feed, as well as limited feed conversion efficiency. Notably, the median extinction impact of ruminant meat far exceeds that of poultry and pork, and is about 100 times higher than that of plant-based proteins.[4] These impacts are also spatially uneven, tending to be higher in tropical regions than in temperate ones, consistent with the concentration of biodiversity in the tropics. Although the estimation of these extinction impacts accounts for species-specific distribution ranges — such that species with narrower ranges are considered more threatened by a given land footprint — we note that the actual consequences for tropical biodiversity at the level of individuals and local populations may be even more severe than these estimates suggest. This is because tropical species often exhibit not only high endemism but also high sensitivity to human disturbance, which can exacerbate population declines beyond what changes in habitat area alone would reflect. Moreover, the ongoing shift of agricultural production from temperate to tropical regions[1] further amplifies the uneven impacts.

Beyond commodity-related and spatial differences, interpretations of telecoupled biodiversity impacts also depend strongly on the scale at which consumption is assessed (Figure 1B). For instance, as a populous emerging economy, India accounts for substantial land consumption, which is projected to increase with economic development and population growth. However, at the household level, per capita land consumption in India remains among the lowest globally (0.19 ha versus a global average of 0.70 ha), reflecting its large population base and low income level.[1] Consistently, per capita food consumption in India is associated with relatively low species extinction impacts, being nearly 30 times smaller than that of the United States.[4] Both total and per capita impacts are essential for sustainability governance: the former reflects aggregate pressure, while the latter captures consumption intensity and equity considerations. Beyond demographic scales, rapid urbanization-driven dietary transitions are also dynamic drivers that reshape telecoupled footprints. In countries undergoing rapid economic growth, shifts towards more resource-intensive diets may substantially increases land demand and biodiversity impacts. Recognizing these cross-

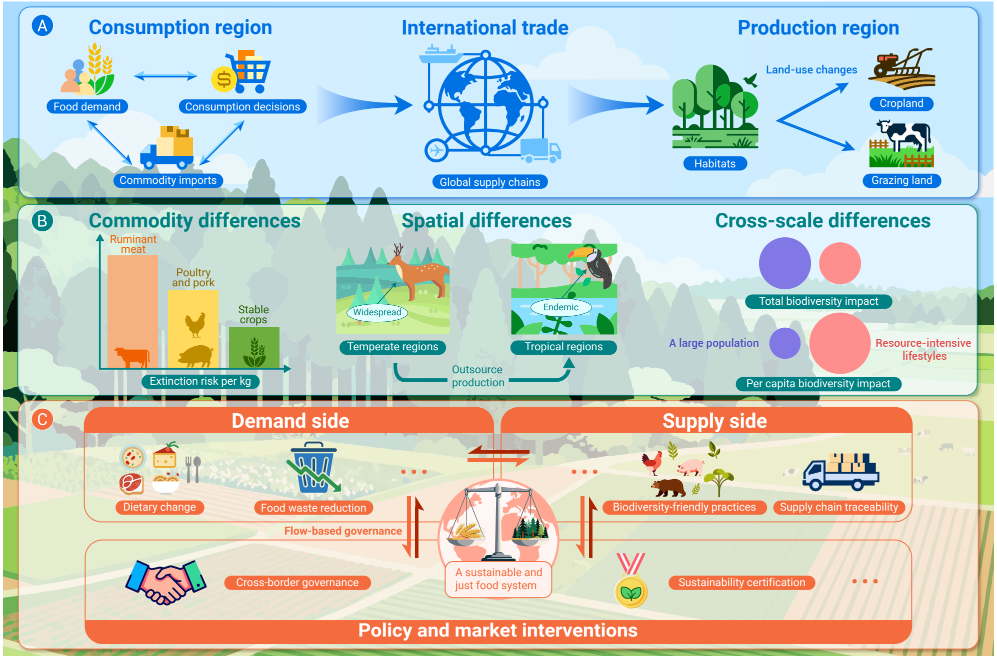

Figure 1. Schematic diagram of telecoupled land footprints and biodiversity impacts in the global food system (A) Land-use changes embedded within the food system. (B) Commodity, spatial, and cross-scale differences in telecoupled biodiversity impacts. (C) Multi-level solutions spanning supply chains to advance food sustainability and biodiversity conservation.

scale differences is essential to avoid misleading comparisons across regions with contrasting demographic and consumption contexts, particularly where food security remains a major concern.

ADVANCING FOOD SUSTAINABILITY AND BIODIVERSITY CONSERVATION IN AN INTERCONNECTED WORLD

With food consumption increasingly affecting biodiversity through telecoupling, biodiversity impacts are determined not only by where food is produced, but also by where and how it is consumed. Focusing exclusively on local conservation risks missing important opportunities to address biodiversity loss embedded within global supply chains. This highlights the need for a shift in the governance of food sustainability and biodiversity conservation from place-based to flow-based approaches.[3] Effective action thus demands multi-level solutions spanning the supply chains (Figure 1C).

On the demand side, dietary shifts toward healthy and sustainable diets, together with reductions in food waste, offer substantial potential to reconcile human health with biodiversity conservation. For instance, adopting the EAT-Lancet Planetary Health Diet in the United States could reduce total land footprint and biodiversity impacts by 44.8% and 29.7%, respectively,[5] while lowering per capita biodiversity impacts by nearly three-quarters.[4] Meanwhile, halving food waste in the United States could lower the total biodiversity impact of food consumption by 17.5%, even in the absence of dietary change.[5]

On the supply side, transforming agricultural production toward biodiversity-friendly practices is essential. Scaling up agroecological approaches, such as diversified cropping, integrated pest management, and reduced agrochemical inputs, helps maintain yields while enhancing biodiversity in agricultural landscapes. Leveraging geoscience tools — including land-system science, cross-scale geographical analysis, and high-resolution remote sensing — combined with trade data and blockchain technology, can reveal the spatial heterogeneity of telecoupled impacts, enable near-real-time monitoring of deforestation-linked commodities, and support traceability across global supply chains. However, the effectiveness of such technological approaches depends on data availability, monitoring costs, and institutional capacity, and if inappropriately implemented, they may risk excluding smallholders in the Global South due to limited access to technology and certification. Supporting the participation of smallholders therefore requires complementary measures, such as low-cost monitoring tools and cooperative-based certification.

These demand-side and supply-side measures can be further reinforced through policy and market interventions. Cross-border governance is critical, including the incorporation of environmental standards into trade agreements and the development of sustainable trade policies, although effective implementation will require addressing coordination challenges, uneven regulatory capacity, and competing economic priorities. Such policies should also account for differences in historical responsibility and development stages, while providing targeted support to regions particularly vulnerable to trade-induced biodiversity impacts. This helps ensure that the food system transformation does not deepen existing inequalities or place disproportionate conservation burdens on specific countries. In parallel, market-based instruments, such as sustainability certification and labeling schemes, can steer consumer choices toward products with lower environmental footprints while encouraging producers to adopt more sustainable practices.

Ultimately, advancing both food sustainability and biodiversity conservation requires moving beyond local perspectives to recognize biodiversity impacts as shared responsibilities embedded within global supply chains. This represents an essential step toward a sustainable and just food system. Importantly, responsibility allocation should account for differences in impact attribution, economic and institutional capacities, and benefit distribution.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.