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The missing markets link in global-to-local-to-global analyses of biodiversity and ecosystem services

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Earth's land resources provide humans with services that are not always recognized and effectively stewarded. Apart from material services (e.g. mushrooms, fish, honey), biodiverse and healthy ecosystems offer several intangible services to humans, such as regulating (weather, nutrient/resources cycling) and non-material services (culture, aesthetics), that current markets do not fully recognize (IPBES 2019). Even the market prices of material services do not reflect the full array of their uses and (environmental) costs. This mismatch of value represents a market failure that arises from the disconnect between who benefits from these services and who provides services. For example, ecosystem externalities (Crocker and Tschirhart 1992) are special types of costs or benefits that result from someone's actions impacting ecosystem processes, which then affect other people's livelihoods. It is increasingly clear that economic activities may alter the ecological equilibrium at the local scale, but the externalities of degraded ecosystems can be felt globally.

In this article we discuss the challenges that frequently arise in global-to-local-to-global (GLG) frameworks when modeling policies aimed at improving land-use change (LUC) while also maximizing the associated benefits from the state of biodiversity and the provision of ecosystem services (BES). A proper analysis of these situations requires a framework that connects global drivers with the responses of living beings at multiple scales; this framework should combine complex systems thinking at a local level with macro-level economic analysis of the land system (Rounsevell *et al* 2012). Land use is directly connected to BES through significant GLG linkages that, if ignored, can result in faulty conclusions or the creation of ineffective policies. Existing literature and models tend to ignore the potential for individual responses in the face of scarce resources, thereby overstating the projected long-run expansion of agriculture. For example, when demand for crops increases at the margin of inaccessible forests, land prices rise sharply and cropland barely expands. While studies addressing these market links are beginning to appear, they are still quite limited. In this paper, we first highlight the need to understand how and when changes in local BES propagate to regional, national and global scales. Next, we briefly describe the challenges in quantifying and modeling the impacts on BES due to inherent complexity in defining them and their multi-dimensional nature. Finally, we highlight the current state of the art in solving these challenges. We lean heavily on examples related to agriculture, because this diverse sector drives the most extensive impacts on BES.

While the impacts on BES of global drivers such as international trade, population growth, technological development or climate change have received strong and increasing attention over the recent decades, relatively few studies have examined the potential propagation of collective local responses into meaningful feedbacks to global drivers (Hertel *et al* 2019). The conditions under which local feedbacks do or do not scale up to have globally important influence on BES remain mostly unclear. This is because there are myriad factors influencing markets with heterogeneous characteristics across small spatial scales. Models that consider variation in these factors are rare, but they can help to identify relevant cases for global BES. For example, Liu *et al* (2017) effectively aggregated farmer responses to water restrictions to show that pursuing sustainable irrigation may erode other development and environmental goals due to higher food prices and cropland expansion. While that study focused on water, and not on biodiversity and other ecosystem services, it lends insights on how accounting for local responses may be important in other sectors.

The main challenge to understanding how markets lead to global changes in BES is identifying the wide array of conditions and processes that determine a local response. In the case of agricultural land use, the responses of a farmer to perceived or expected climate change (i.e. adaptation) can include changing farming practices, switching crops, selling or abandoning land, or continuing current practices. Changes in farming practices in a region, and consequent changes in the provision of goods and services from that region, could feed back to global crop prices and global climate, if the changes were adopted over a large enough region or if the region is a dominant supplier of a particular crop. However, individual farmer decisions will be influenced by a complex mix of socioeconomic factors (potentially influenced by local and national governments and organizations), environmental factors, and, importantly, the degree to which the farmer is vested in land stewardship and has access to relevant information.

The full range of social, political, economic, and environmental conditions that influence any one farmer is not included in any economic or Earth system model, or even any Integrated Assessment Model (Rieb *et al* 2017). Even if all of these conditions could be included in a single model, many of the conditions experienced by farmers would be associated with a large degree of uncertainty. Local impacts of societal drivers have been estimated globally for a few ecosystem services (e.g. fertilizer pollution and water quality regulation, Chaplin-Kramer *et al* 2019), but there remains a large research gap. Studies of BES typically use spatially explicit analyses using small-scale pixels that are aggregated to get regional, national, and global estimates. However, most of these analyses are based in the natural sciences, and thus results have rarely been used to analyze market responses at all scales through price effects and the consequent impacts on local-scale decisions.

We present four complexities associated with case studies that describe approaches to protecting BES in diverse landscapes and contexts within the GLG framework: heterogeneity in local markets; additionality; spillover and leakage effects; and unintended consequences.

The first challenge in designing and implementing BES conservation programs with GLG perspective is representing the heterogeneous dynamics and restrictions of local markets. For example, the impact of conservation programs that require farmers with limited employment potential to remove land of high BES value from production. Indeed, agricultural labor markets are often sticky, i.e. mobility of potential workers across regions is limited, but these market dynamics vary by location especially in highly mechanized farms. Ray *et al* (2022) model these heterogeneous dynamics across counties in the USA to show that failing to account for labor market rigidities may lead to overstate the impacts of global price shocks and conservation polices on crop production and LUC. The characteristics of rural communities also shape the type of involvement in conservation policies, given the opportunity cost of farming. In the USA Corn Belt, strategies to promote agricultural practices that favor BES have focused on voluntary rather than regulatory approaches but adoption of such practices remains low. Barriers include perceptions of costs vs. incentive payments, risks, and near-term returns that are required given the high prevalence of rented farmland (Ranjan *et al* 2019).

A second challenge in designing BES conservation programs with GLG perspective is the need to identify and address additionality concerns. Payment for ecosystem services (PES) programs compensate landowners for preserving BES on their land and have been shown to improve environmental outcomes (Engel *et al* 2008). PES programs address externalities by altering the economic incentives private actors face, while allowing these actors to decide whether and how much to change their behavior (Jack *et al* 2008). The implementation of PES programs requires information to systematically cross-scale from the most local level to more aggregate levels (Wegner 2016). One widely implemented, cross-scale PES program is that of the Water Fund (Brauman *et al* 2019). Water Funds are a financial and governance model that connects cities, development banks, or other entities to upstream landowners who make choices that affect downstream water quality. These collective-action funds transfer pooled resources to compensate upstream owners to protect water quality by keeping their farmland forested. However, to achieve these aims in a cost-efficient way, it is important to ensure that the BES benefits being paid for under a PES scheme would not have happened in absence of the payment. The 'additionality' of such benefits, as it is referred to, becomes especially challenging to identify in large-scale PES programs that aim to protect more than just the highest-valued lands globally.

The third challenge represents market responses to policies that may be positive at the project location but cause increased loss of BES elsewhere due to shifting production patterns. Assessing the effectiveness of PES programs at aggregate or global scales requires an analysis of how changes brought about by PES may cause changes in other regions. 'Leakage' effects may occur when PES in natural land cause reductions in agricultural outputs. For example, if the goal of the conservation action is to increase the wellbeing of a migratory species, then its complete route must be

Table 1. Environmental and economic impacts of two different policies to mitigate deforestation from oil palm production in Malaysia and Indonesia (M&I) as modeled by Taheripour *et al* (2019). They considered two policies aimed to achieve the same end goal of maintaining 2011 levels of oil palm production (domestic palm oil production TAX in M&I, international TARIFF on palm oil imports by rest of the world) while offering at the same time a subsidy to freeze forestland.

Metric	Malaysia and Indonesia (M&I)		Global	
	TAX	TARIFF	TAX	TARIFF
Avoided forest loss (Mha)	3.1	3.2	2.5	2.5
Market-based welfare impacts (M USD)	1053	−4693	−5532	−7398

considered (Albers *et al* 2022): payments to reduce agricultural activity in high-use regions for the species (stopovers) may increase the profitability of agricultural goods produced in other low-use regions along migratory pathways. The reallocation of agriculture activity could potentially block the completion of the migration in the absence of suitable alternative routes for the species. Such leakage effects are not easy to model although implementation of BES conservation programs across scales can benefit from leveraging satellite and aerial imagery/data to provide scalable and robust enforcement (Wünscher *et al* 2008).

A fourth challenge is that BES conservation policies may have multiple unintended impacts. Taheripour *et al* (2019) demonstrated this by examining policies to mitigate deforestation in Malaysia and Indonesia (M&I). The authors used the Global Trade Analysis Project (GTAP) model to assess two conservation policies in terms of their effectiveness in avoiding forest loss but also the differential welfare impacts (table 1). While BES were not evaluated as an explicit metric, forest loss was considered a direct proxy of biodiversity loss in this region (Hughes 2017). Taheripour *et al* (2019) showed that the market-based welfare impacts were all negative at the global level because the policies restricting palm oil production affect prices of goods and services, wage rates, returns to agricultural land, and gross domestic product (this impact is negative as it ignores the climate mitigation benefits of reducing deforestation). When M&I impose a production tax on oil palm cultivation (TAX policy), this raises palm oil prices globally, increasing export prices and improving terms of trade for M&I but reducing economic welfare for rest of the world. In contrast, if the rest of the world imposes a tariff on palm oil imports (TARIFF policy), that reduces global demand for oil palm, decreasing palm oil export prices for M&I, leading to worsening terms of trade (and welfare impacts) for the region. Therefore, the results for the M&I show an important tradeoff, with TAX having a net benefit, while TARIFF has a net welfare cost (table 1).

Most of the GLG frameworks studying impacts on BES rely on models that estimate LUC in different regions of the world with imposed drivers such as population growth, and linking such models with ecological models to predict the impact on BES. To account for the missing markets link in GLG analyses of BES and to address the above four challenges, the GTAP-AEZ model (Hertel *et al* 2009) is increasingly being used as a novel solution. The standard GTAP model (Corong *et al* 2017) is a multi-sector and multi-country general equilibrium model (GEM) that captures economic interactions between agents and feedback effects from factor and commodity markets at both national and global levels. Instead of national scale, the GTAP-AEZ model operates at a finer land type (agro-ecological zones; AEZ) resolution, thereby making it more appropriate for capturing local BES variations and national and global economic effects associated with LUC. For example, Johnson *et al* (2021) linked GTAP-AEZ with a high-resolution spatially explicit ecosystem services module called the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model (Chaplin-Kramer *et al* 2019) to assess the performance of four policies: agricultural subsidy removal, investing in research and development for agricultural intensification, and two funding schemes for PES programs (own nations' funding vs global transfer payments). The linked models calculate the supply of pollination, timber production, climate regulation from carbon sequestration, and marine fisheries, accounting explicitly for the location of beneficiaries (e.g. farms adjacent to pollinator habitat). The main advantage of GTAP-InVEST is that it captures not only global-to-local but also local-to-global impacts, where the change in ecosystem service are aggregated up to AEZ regions and endogenously affect economic productivity (figure 1). Integrated earth-economy modeling of this type is still very much in an early stage and considerable work needs to be done to include more ecosystem services, add detail on the how BES changes can be meaningfully connected to parameters in GEMs, increase compatibility with national-level GEMs, and to reframe the model in a dynamic setting.

In sum, research capable of aggregating the local market responses affecting BES to the global level remains a critical need. The existing studies dealing with this research gap are limited in number and scope. Here, we highlight that this aggregation

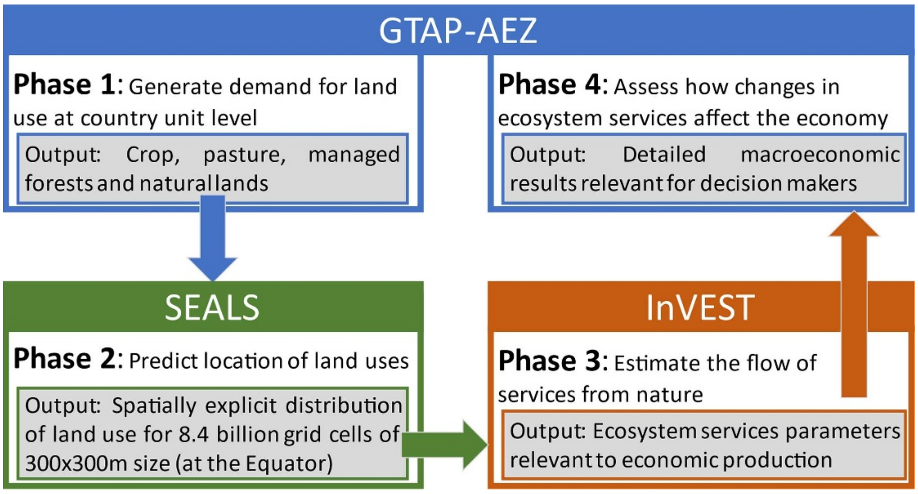

Figure 1. GTAP-InVEST model addresses missing markets link in GLG analyses of BES. To analyze economic and BES interactions, Johnson *et al* (2021) carried out three modeling steps: (i) the GTAP model is first simulated to provide projections of regional land use per agro-ecological zones (AEZ) for cropland, pastureland, managed forests, and natural land at the national level; (ii) downscale the national AEZ LUC to local grid level using the spatial economic allocation landscape simulator (SEALS); (iii) upscale the local InVEST impacts and implement as shocks to the GTAP model to assess how changes in local ecosystem services affect the national and global economies through changes in commodity supply, factor and commodity markets, and global trade and investments.

problem is particularly difficult for several reasons but recently developed models such as GTAP-AEZ are capable of capturing market links, and, if linked to spatially explicit ecosystem services models such as InVEST, can allow for analysis of the impacts of policies aimed at improving BES outcomes. Future studies should expand the application of such models using different indicators of BES to analyze alternative policies and their impacts at different geographic scales. The results from these models can help stakeholders in designing effective win-win policies and avoid trade-offs, thereby contributing towards progress on United Nations Sustainable Development Goals and Post-2020 Biodiversity Framework.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare no competing interest.

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