# A review of global-local-global linkages in economic land-use/cover change models

Environmental Research Letters

TOPICAL REVIEW

# A review of global-local-global linkages in economic land-use/cover change models

Thomas W Hertel[1], Thales A P West[2], Jan Börner[2,4] and Nelson B Villoria[3]

[1] Department of Agricultural Economics, Purdue University, West Lafayette, IN 47907-2056, United States of America
[2] Center for Development Research (ZEF), University of Bonn, Bonn, D-53113, Germany
[3] Department of Agricultural Economics, Kansas State University, Manhattan, KS 66506, United States of America
[4] Institute for Food and Resource Economics (ILR), University of Bonn, Bonn, D-53115, Germany

**E-mail:** hertel@purdue.edu

**Keywords:** global change drivers, local sustainability, land use change, leakage, spillovers

OPEN ACCESS

RECEIVED
11 May 2018

REVISED
4 March 2019

ACCEPTED FOR PUBLICATION
6 March 2019

PUBLISHED
3 May 2019



## Abstract

Global change drivers of land-use/cover change (LUCC) like population dynamics, economic development, and climate change are increasingly important to local sustainability studies, and can only be properly analyzed at fine-scales that capture local biophysical and socio-economic conditions. When sufficiently widespread, local feedback to stresses originating from global drivers can have regional, national, and even global impacts. A multiscale, global-to-local-to-global (GLG) framework is thus needed for comprehensive analyses of LUCC and leakage. The number of GLG-LUCC studies has grown substantially over the past years, but no reviews of this literature and their contributions have been completed so far. In fact, the largest body of literature pertains to global-to-local impacts exclusively, whereas research on local feedback to regional, national, and global spheres remain scarce, and are almost solely undertaken within large modeling institutes. As such, those are rarely readily accessible for modification and extension by outside contributors. This review of the recent GLG-LUCC studies calls for more open-source modeling and availability of data, arguing that the latter is the real constraint to more widespread analyses of GLG-LUCC impacts. Progress in this field will require contributions from hundreds of researchers around the world and from a wide variety of disciplines.

## 1. Background and motivation

The world's land resources are critical to the attainment of various *Sustainable Development Goals* (SDGs) of the *Agenda* 2030 (Obersteiner *et al* 2016), but are under intense pressure from growing populations and rising per-capita consumptions (Godfray and Garnett 2014). Can the future demands for food security, renewable energy, clean water, conservation of biodiversity, climate change mitigation and poverty reduction be reconciled? Are we counting on the same area of land to satisfy conflicting SDGs? The sustainable development challenge—as viewed through the lens of the world's land resources—is a particularly 'wicked' problem because global sustainability solutions depend on national, regional or local circumstances, requiring fine-scale analyses of land-use/cover change (LUCC)[5].

Even as local LUCC processes are often driven by remotely emanating global forces, regional responses to these pressures and the pursuit of local sustainability goals can, in turn, result in cross-border and international leakage (spillover) effects[6], i.e. land initiatives in one place stimulating LUCC elsewhere (Delzeit *et al* 2018). Such leakage from national or subnational policies may affect the wider availability of land-based commodities and their prices, as well as local, regional, and global social and environmental conditions. Addressing these issues requires a multiscale approach that recognizes the linkages between global drivers and local responses (Rounsevell *et al* 2012), and their feedback at the regional, national, and global levels, i.e. *global-to-local-to-global* (GLG) analyses. While this terminology has gained recent

[5] Following Lambin *et al* (2003) 'land use is defined by the purposes for which humans exploit the land cover,' whereas 'land cover is defined by the attributes of the earth's land surface.'

[6] Following Meyfroidt *et al* (2013), leakage is understood here as a form of land use displacement, where an intervention intended to reduce the environmental impact of a given land use leads to a shift of this impact to another location.

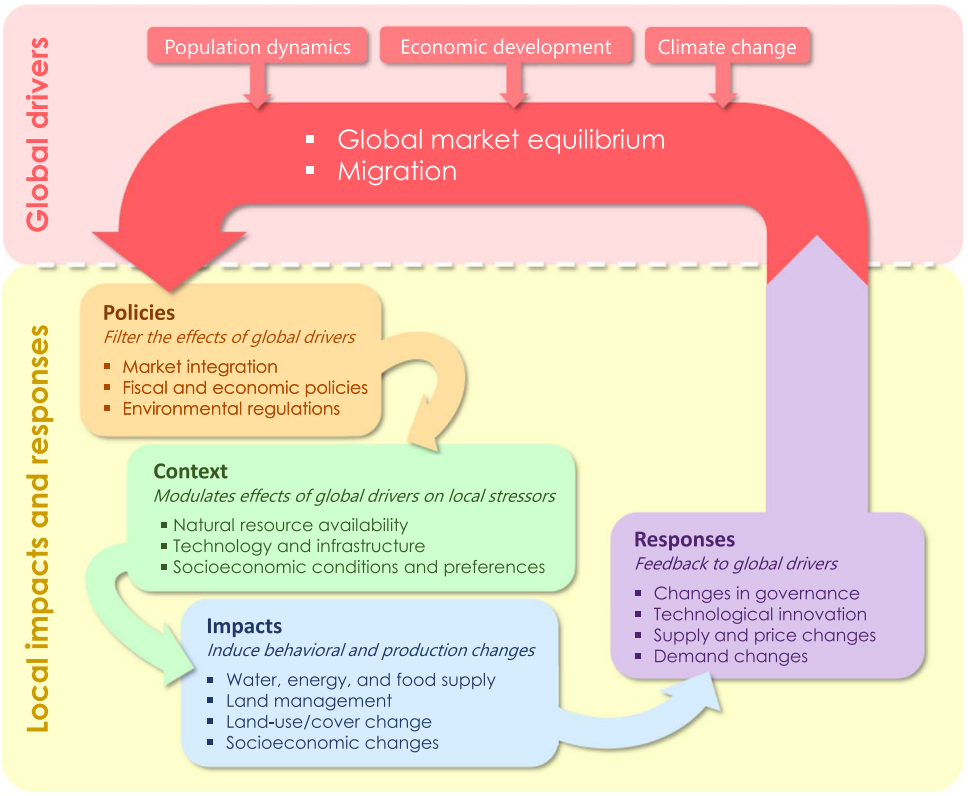


**Figure 1.** Conceptual framework for global-to-local-to-global linkages of land-use/cover change. Global drivers, including population, income, climate, and technology drive the global supply and demand for land-based products, resulting in new market equilibria, price changes, and migration. When filtered through the national and subnational policies, global effects result in local stresses and responses which affect enterprises, households, and the environment, leading to policy changes and innovations, as well as to adjusted supplies and demands for land-based goods. Finally, the resulting changes in land use/cover attributed to both local and global factors may feedback to the global context.

attention in other fields, e.g. medical geography (Blatt 2015), it remains incipient in the LUCC literature.

Within the GLG-LUCC framework outlined in figure 1, global drivers represented by population dynamics, economic (and technological) development, and climate change shape global markets and migration patterns (Hunter *et al* 2015). These drivers affect global supply and demand for land-based resources, resulting in changes in international prices, as well as cross-border flows of commodities, capital and labor. The impacts from those drivers are filtered by national and subnational environmental and economic policies and institutions (e.g. exchange rate and trade regulations as well as land tenure) and market integration. National and subnational contexts, defined by natural resource availability, infrastructure and technology transfer, socioeconomic conditions (e.g. population size, income and education levels) and preferences (e.g. dietary choices, environmental and social awareness), modulate the impacts of global drivers on regional or local stressors. Once the impacts of global drivers reach domestic producers and consumers, they may induce production and behavioral changes related to land use/cover and socioeconomic preferences (e.g. for animal-sourced food) and conditions (e.g. income growth and energy consumption). Negative impacts can result, for example, in over-exploitation of natural resources, agriculture-induced water scarcity, higher food prices, exacerbated land conflicts, and socioeconomic hardship. Consequently, the impacts of global drivers are often followed by national or subnational responses such as changes in governance and regulations, as well as technological innovation, which can, in turn, feedback to the global level (figure 1).

The GLG-LUCC framework acknowledges that local impacts and responses can have important implications, not only locally or regionally, but also at the national and—often overlooked—global levels. If these responses are strictly localized, then it is unlikely that the feedback to international prices will be significant. However, if many localities respond to the influence of global drivers, GLG-LUCC feedbacks might affect global environmental and economic dynamics substantially. An example of this is provided by Liu *et al* (2017) who examine the impact of widespread irrigation water withdrawal restrictions on global food prices, food security and cropland conversion.

This review presents a summary of the recent history and status quo of the LUCC literature that has addressed key GLG linkages and feedbacks illustrated in our proposed GLG-LUCC framework (figure 1).

Our summary is complemented by a systematic review of recent and prominent peer-reviewed publications. By focusing on economic modeling of LUCC, our review does not capture context-specific social and political forces that often initiate LUCC at agricultural frontiers. As such, the lower panel of figure 1 identifies a set of forces that influence land use decisions at national level after land claims have been established. Finally, the review aims to identify literature gaps and outline future research directions to improve understanding and integrate the GLG framework into LUCC studies.

## 2. Methods

We conducted a systematic search for peer-reviewed articles published between 2009 and 2018 in ISI Web of Knowledge. We adopted a Boolean searching key[7] to filter unrelated climate, biodiversity, hydrology, and geology studies from the ones focused on LUCC. This search identified 727 articles, which were successively screened based on their titles, keywords, and abstracts, in accordance with the PRISMA approach for systematic reviews (Chatterjee *et al* 2018). For instance, many identified articles focused solely on global-to-local links, with no regard to local feedback, whereas others presented merely theoretical perspectives (e.g. on environmental governance and certification schemes) or even, despite our searching key, addressed issues unrelated to GLG-LUCC (e.g. satellite-mapping techniques, lifecycle analysis, and biological, geological or climate studies) or issues related to urbanization, which is considered out of the scope of this review. Those articles were excluded. Lastly, we adopted an additional filter based on the number of citations per year ($\geqslant 10\,\mathrm{yr}^{-1}$) as an attempt to select the most prominent studies in the field (articles published in 2018 were scrutinized independently of the number of citations). The remaining 96 publications were added to a preliminary list for further screening. Of the list of identified studies, 81 articles addressing issues relevant to GLG linkages are referenced in this review. In addition to the systematically-selected recent publications, we also included what we consider key 'building block' studies (70 in total) that developed the basis for GLG analyses in the field of LUCC to provide a historical perspective on the topic or that complements our discussion, which led to the 151 articles cited in this review (figure A1). Table 1 provides an overview of the current GLG-LUCC literature based on this survey, along with key gaps and a discussion of future directions for GLG-LUCC studies, to which we refer in the subsequent sections of this review.

[7] *TS = (('land-use change' OR 'land use change' OR 'land-cover change' OR 'land cover change' OR 'land-use/cover change' OR 'land use/cover change' OR deforestation) AND model AND (economic OR simulation) NOT hydro* NOT runoff NOT fluvial NOT fish* NOT wildlife NOT habitat NOT species NOT precipitation NOT urban NOT climatolog* NOT atmospher* NOT meteorolog* NOT water* NOT wind NOT air NOT albedo NOT chemistry NOT physics NOT soil NOT geomorpholog*).*

## 3. Results and discussion

Food production is one of the most common land uses worldwide. Agricultural products are widely traded, and cropland conversion for farming is one of the major drivers of LUCC, particularly in the tropics (Busch and Ferretti-Gallon 2017, Curtis *et al* 2018). As a result, and due to the focus of the modeling literature, our systematic review was largely populated by global agro-economic studies based on computable general equilibrium (CGE) and partial equilibrium (PE) models, with a lesser representation of studies focused on forestry or other land-based sectors and alternative methodologies (e.g. empirical studies).

### 3.1. Global LUCC models: a historical perspective

The first LUCC models, dating back to the 1960s, focused on the quantification of world food budgets and prospects for food production, emphasizing food availability rather than land uses (FAO 1962). The food crisis of the early 1970s led to the *Club of Rome* report (Meadows *et al* 1972) and an emphasis on finite land resources which were expected to be overtaken by a rapidly growing population. However, as with Malthus' (1798) original predictions, this work was eventually discredited as being overly pessimistic. The 1980s saw a flourishing of global agro-economic CGE and PE models such as IMPACT (Rosegrant *et al* 2008), GOL (Rojko 2017) and BLS (Fischer and Frohberg 1982). Of those, only the latter acknowledged the finite nature of land resources through endowment constraints considered at an aggregated regional level.

It was not until the 1990s that global LUCC models started to focus explicitly on the competition for land between agriculture and other activities within diverse *agro-ecological zones* (AEZs), such as the FARM model. FARM was developed at the United States Department of Agriculture (Darwin *et al* 1995) and built on the *Global Trade Analysis Project* (GTAP) database and modeling framework (Hertel 1997). The model was used by Darwin *et al* (1995) to investigate future climate impacts not through productivity shocks to existing crops (which was commonly studied), but rather as changes in the distribution of lands across AEZs. This novel, land-focused approach to global modeling sharpened the focus of LUCC models to AEZ land endowments, the activities undertaken within different AEZs, and their simulated responses to climate change. Findings from these type of studies typically emphasized the role of international trade in mediating LUCC and leakage effects between regions when the productivity and abundance of individual nations' land endowments are differentially affected

by biophysical forces, policies, and technological change (Reilly *et al* 2003, Stevenson *et al* 2013).

Roughly in parallel to the development of the FARM model, Sohngen and Mendelsohn (1998) introduced the *Global Timber Model* (GTM). By incorporating forest growth and harvesting dynamics into an economic model, the authors were able to examine a wide range of LUCC issues related to the forest sector. The GTM became an important tool for understanding the potential for forest carbon sequestration as part of a more comprehensive global climate policy (Sohngen 2010). The GTM is driven by global projections of growth in income and population. However, since the model represents consumption with one composite global timber demand function, it has been used less extensively for global leakage assessments since it does not specifically capture bilateral trade between regions of the world. Of necessity, it also aggregates regions to a much higher degree due to the computational challenges presented by a fully dynamic economic model (Sohngen and Mendelsohn 2003).

Growing interest in more comprehensive assessments of climate change mitigation (i.e. extending beyond fossil fuel emissions) promoted a series of long-term research projects aimed at building databases and modeling infrastructure for the analysis of land-based interventions (Hertel *et al* 2009). The GTAP-AEZ database and modeling framework resulted from that initiative (Lee *et al* 2009), forming the basis for much of the global LUCC studies focused on agricultural trade since that time (Schmitz *et al* 2014). Given the high degree of disaggregation (the current GTAP-AEZ database considers 140 national/subnational regions, with up to 18 AEZ each), the comprehensive treatment of greenhouse gas (GHG) emissions, the national representation of consumption, and the bilateral treatment of trade, the GTAP-AEZ-GHG models quickly assumed global prominence in leakage and indirect LUCC studies, in particular with the implementation of new biofuel mandates in the US and EU (Al-Riffai *et al* 2010, Taheripour and Tyner 2013). Examples of other global LUCC models based on the GTAP framework are AIM (Fujimori *et al* 2017), MAGNET (van der Hilst *et al* 2018), ENVISAGE (van der Mensbrugghe 2013), EPPA (Melillo *et al* 2009), GCAM (Calvin *et al* 2013), and GTEM (Porfirio *et al* 2018). A number of comparisons among these models can be found in the literature (Schmitz *et al* 2014, von Lampe *et al* 2014, Alexander *et al* 2017, Popp *et al* 2017).

Another direction of global LUCC research over the past decade emanated from the earth system modeling literature, in particular, from improved representations of terrestrial ecosystems and the carbon fluxes associated with LUCC processes (Hurtt *et al* 2011). That literature is traditionally based on global gridded analyses and the developments in global circulation models undertaken in support of climate-related research (Intergovernmental Panel on Climate Change IPCC 2014). The initial demand for global-gridded LUCC projections was supported by downscaling regional results to the grid-cell level, allowing for the exploration of GLG-LUCC linkages at much higher resolutions (Reilly *et al* 2012, Schmitz *et al* 2014, Doelman *et al* 2018, Porfirio *et al* 2018). In addition to downscaling results, much of the literature also focused on upscaling local effects of climate impacts on land-based activities from global grids (Rosenzweig *et al* 2014).

At the regional scale, a number of influential gridded simulation models have been developed and applied to assess future LUCC at high-spatial resolution and under alternative economic and policy scenarios (Verburg *et al* 2002, Soares-Filho *et al* 2006, Lapola *et al* 2010). A notable effort in this area is the *Dynamic Conversion of Land Use and its Effects* model (Dyna-CLUE) presented by Verburg and Overmars (2009). Dyna-CLUE integrates the allocation of top-down, multi-sectoral demand-driven LUCC with a bottom-up determination of conversions for specific land-use transitions at the grid-cell level and time considerations for natural vegetation regrowth. This 'soft-linking' approach allows accounting for very detailed local and regional determinants of LUCC, but tends to ignore local-to-global feedback (Rutten *et al* 2014).

### 3.2. A gridded view of the world in economic LUCC models

Until recently, most of the global LUCC analyses relied on the downscaling of regional results in order to make predictions at the grid-cell level. Where gridded biophysical model results were required for use in the global model, they were aggregated to the level of the regions considered by the global models. Such approaches clearly limit the scope for full exploration of GLG linkages and raises questions of conceptual, data, and computational consistency. In response to these limitations, the Potsdam Institute for Climate Research (PIK) group developed the MAgPIE model (Lotze-Campen *et al* 2008), the first grid-based, global LUCC model incorporating a bottom-up agro-economic equilibrium model coupled with a global dynamic vegetation, hydrology, and crop simulator, the LPJmL (Bondeau *et al* 2007). The objective function of MAgPIE is to satisfy agricultural demand for food, feed, bioenergy, and materials from ten world regions at minimum global costs (including the cost of capital, labor, inputs, investments in technology, and mitigation of GHG emissions), and given biophysical and socio-economic constraints. Cost-effective LUCC decisions at the grid cell-level are endogenous and based agricultural intensification, expansion, and relocation or trade (Kriegler *et al* 2017).

MAgPIE was later coupled with REMIND, also developed at PIK, resulting in the integrated assessment modeling framework REMIND-MAgPIE (Popp *et al* 2011). REMIND is an energy-economic equilibrium/macroeconomic growth model based on

**Table 1.** Analyses of global-to-local-to-global impacts of land-use/cover change.

| Main global drivers | Local stressors | Local response | Global-to-local linkage | Local-to-global feedback | Geographic scope | Methods | References |
|---|---|---|---|---|---|---|---|
| Climate change mitigation | Fossil fuel consumption and GHG emissions | Biofuel mandates | National or regional biofuel targets increase land demand for energy crops locally and globally, leading to LUCC leakage | Local LUCC shifts supply of energy crops, altering regional and global market equilibrium, and increase local GHG emissions, contributing to global warming | United States | PE and statistical models | Hertel *et al* (2010b), Villoria and Hertel (2011), Wang *et al* (2011), Mosnier *et al* (2013), Chen and Khanna (2018), Somé *et al* (2018), Garcia and You (2018) |
| | | | | | European Union | PE and CGE models | Al-Riffai *et al* (2010), Britz and Hertel (2009), Laborde and Valin (2012), Somé *et al* (2018), Garcia and You (2018) |
| | | Carbon pricing | Supply decrease of agricultural goods at national or international scale increase cropland demand in other regions or countries, leading to LUCC leakage | Local LUCC shifts supply of agricultural goods, altering regional and global market equilibrium, and increase local GHG emissions, contributing to global warming | Global | PE model | Popp *et al* (2014), Havlik *et al* (2014), Stevanović *et al* (2017), Lungarska and Chakir (2018) |
| | | | Changes in regional timber production | Local increases in timber production lead to GHG emissions, contributing to global warming | Bolivia | Dynamic optimization model | Sohngen and Brown (2004) |
| Economic development and population growth | (Illegal) conversion of forests to cropland | New land-use regulations and conservation policies | Supply decrease of agricultural goods at national or international scale increase cropland demand in other regions or countries, leading to LUCC leakage | Local LUCC shifts supply of agricultural goods, altering global market equilibrium, and increase GHG emissions, contributing to global warming | Argentina, Bolivia, Paraguay, and Brazil | Statistical model | le Polain de Waroux *et al* (2017), Fehlenberg *et al* (2017) |
| | | | | | Brazilian Amazon | PE and statistical models | Barona *et al* (2010), Arima *et al* (2011), Cohn *et al* (2014), Soterroni *et al* (2018) |
| | | | Supply decrease of gold at national scale increase | Local LUCC increase gold supply, altering regional | French Guiana and Suriname | Statistical model | Dezecache *et al* (2017) |

**Table 1.** (Continued.)

| Main global drivers | Local stressors | Local response | Global-to-local linkage | Local-to-global feedback | Geographic scope | Methods | References |
|---|---|---|---|---|---|---|---|
| | Illegal conversion of forests to gold-mining fields | New land-use regulations and conservation policies | demand in neighboring countries, leading to LUCC leakage | market equilibrium, and GHG emissions, contributing to global warming | | | |
| | Globalization | Trade liberalization | Supply increase of agricultural goods at the international level affect domestic cropland demand, leading to LUCC leakage | Local LUCC shifts supply of agricultural goods, altering global market equilibrium, and increase GHG emissions, contributing to global warming | Global | PE model | Schmitz *et al* (2012) |
| | Changes in consumption and dietary preferences | Increase of domestic demand for meat and dairy products | Increase of international demand for meat and dairy products, leading to LUCC leakage | Local LUCC shifts supply of soy, altering global market equilibrium, and increase GHG emissions, contributing to global warming | China | Descriptive statistics and CGE model | Yu *et al* (2013), da Silva *et al* (2017), Yao *et al* (2018), Delzeit *et al* (2018) |
| | Low agricultural productivity | Technological innovation (e.g. new crop varieties, changes in production and management practices) | Productivity increase may reduce cropland demand at a global scale; non-market mechanisms induce global technology transfer with LUCC and leakage implications | Local gains in productivity encourage LUCC at the national scale and increase GHG emissions, contributing to global warming | Latin America, Sub-Saharan Africa, Middle East, and South Asia | Descriptive statistics and PE, CGE, and conceptual models | Villoria *et al* (2013), Stevenson *et al* (2013), Dietrich *et al* (2014), Gasparri *et al* (2016) |

eleven world regions, a variety of fossil, biogenic, nuclear and renewable energy resources and technologies, associated GHG emissions, path dependencies, and the dynamics of economic growth and international trade (Leimbach *et al* 2010). While most of the applications of MAgPIE investigated the impacts of climate change on agriculture (Nelson *et al* 2014, Wiebe *et al* 2015), others have use it to explore issues related to endogenous technological changes (Dietrich *et al* 2014), trade liberalization (Schmitz *et al* 2012), GHG emissions mitigation policies (Stevanović *et al* 2017), and socio-economic development pathways (Kriegler *et al* 2017, Popp *et al* 2017).

Modelers from the *International Institute for Applied Systems Analysis* (IIASA) represent the second group to become deeply involved in global gridded modeling of GLG-LUCC processes, in particular with the development of the GLOBIOM model (Havlik *et al* 2013)—currently covering 30 world regions. Some of their work on climate change impacts showed that mitigatory GHG emission policies may have a greater impact on food security at mid-century than global warming itself (Havlik *et al* 2015). Variations of GLOBIOM have also been used to study national and subnational impacts of climate, energy, and conservation policies on LUCC, e.g. GLOBIOM-Brazil (Soterroni *et al* 2018) and GLOBIOM-EU (Frank *et al* 2016). Both the MAgPIE and GLOBIOM models have evolved to support a broader range of land-related studies, including analyses of the SDGs in the context of alternative future pathways of global economic growth and carbon emissions (Obersteiner *et al* 2016, Stevanović *et al* 2017).

The ever-growing demand for spatial disaggregation has been constrained both by data availability and by computational considerations (Lee *et al* 2015). Yet, given the rapid pace of improvement in both software and hardware, it is reasonable to expect computational constraints to diminish significantly in the near future. However, the collection and access to disaggregated (local) socioeconomic data is another matter. Hence, with some exceptions including agent-based modeling methods (Valbuena *et al* 2010, Murray-Rust *et al* 2014, West *et al* 2018), grid-based models coupled with agro-economic PE or CGE models are currently at the frontier of global and regional GLG-LUCC analyses. By integrating local biophysical, economic, and institutional information into a global framework, complex gridded models—developed by large research institutes and teams of collaborators—represent the most suitable approach to explore both the global drivers of local LUCC, as well as the feedback from national and subnational interventions to the global level (Schmitz *et al* 2014, von Lampe *et al* 2014, Alexander *et al* 2017, Popp *et al* 2017).

### 3.3. Global drivers in GLG-LUCC studies

The global-to-local focus dominates the LUCC literature; these studies conceptualize or quantify the effect of exogenous global drivers on national or subnational contexts. Climate, economic development, and population are commonly represented global drivers in LUCC studies, particularly among the ones based on agro-economic equilibrium models (Schmitz *et al* 2012, Stevenson *et al* 2013, von Lampe *et al* 2014, Alexander *et al* 2017, Popp *et al* 2017, Delzeit *et al* 2018, Yao *et al* 2018). Climate change affects the competition for land by altering local crop productivity and, consequently, the supply and demand equilibrium of land-based products in domestic and international markets. Similarly, population growth (or decline) and economic development, leading to changes in income, labor, productivity/technology, consumption, and dietary patterns (Havlik *et al* 2014, Doelman *et al* 2018, Lanz *et al* 2018, Lefèvre *et al* 2018, Yao *et al* 2018), also affect the national demand for agricultural commodities, such as livestock and biofuels, and again market equilibrium (Yu *et al* 2013, Chen and Khanna 2018, Lungarska and Chakir 2018). Nevertheless, although agro-economic models tend to consider the same global LUCC drivers, projections from distinct models are often in disagreement with each other (von Lampe *et al* 2014, Alexander *et al* 2017).

A landmark effort, coordinated by the *Agricultural Modeling Intercomparison Project* (AgMIP), sought to compare LUCC trajectories to 2050 based on simulations from 10 global agro-economic models, global drivers were represented by population, GDP, and biophysical yields (Schmitz *et al* 2014). Under *Shared Socioeconomic Pathway* (SSP) scenarios (O'Neill *et al* 2014), this model ensemble projected a mean cropland expansion (2005–2050) of nearly 200 Mha, with extremes (individual model projections) ranging from a decline of 50 Mha to an increase of more than 400 Mha. The authors also simulated the incremental impact of climate change on cropland in 2050. All models projected an increase in cropland as a result of climate change (potentially beneficial effects of elevated $CO_2$ concentrations on plant growth were omitted), and all but two forecast incremental cropland growth of 10% or less by 2050. Contrasting results across global LUCC model projections were also reported by others (Alexander *et al* 2017, Popp *et al* 2017).

A series of studies in the literature investigated the reasons for the disagreements in global LUCC model simulations. Based on the work of Schmitz *et al* (2014), von Lampe *et al* (2014) identified contrasting model definitions for commodity prices and (hidden) basic model parameters such as income and price elasticities, that define market behavior, besides data limitations on economic behavior and biophysical drivers. In addition, Hertel *et al* (2016) found that the ten models employed in the AgMIP inter-comparison exercise apply very different assumptions about the potential for intensification of production and cropland expansion. Moreover, in a recent study based on simulations

from 18 LUCC models, the authors ascribed much of the differences in land-cover area projections (particularly in croplands) with the lack of consistency in the definitions of pasture and forest (Alexander *et al* 2017). The same authors also highlighted that similar model types are also more likely to share similar underlying assumptions and other commonalities, e.g. same model calibration data.

Which of the global drivers is most important in determining global—and regional—patterns of LUCC? Baldos and Hertel (2016) offer a decomposition of the drivers behind global cropland change over the period 1961–2006. They find that population growth was the dominant driver—far more important than income growth—with improved technology offsetting about half of the upward pressure on cropland expansion stemming from the population and income growth. This stands in contrast to the postulated 'Jevons paradox,' which suggests that improved technology might actually increase cropland use (Alcott 2005). These authors also consider LUCC projections to mid-century, for which they conclude that income growth will rival population growth as the major driver of future cropland expansion. This expected change is due to two main factors: (a) a slowdown in global population growth, and; (b) a shift of the composition of population growth towards low-income regions (e.g. Africa), where current per-capita food consumption remains modest. Projections also suggest that bioenergy, water scarcity, and urbanization are likely to contribute far less to global LUCC.

While global drivers, such as population and technology, are often exogenous in LUCC studies and, in particular, in global agro-economic models, exceptions can be found. For example, increases in crop yield due to technological change are endogenous in MAgPIE (Popp *et al* 2014). Demand for food and materials are often exogenously calculated, based on historical consumption patterns and future demand expectations driven by population and income changes (Schmitz *et al* 2012, Stevanović *et al* 2017, Chen and Khanna 2018, Lungarska and Chakir 2018), which can respond endogenously to price variations (Havlik *et al* 2014). Similarly, most models include an endogenous component to yields, allowing adjustments to input and output prices (von Lampe *et al* 2014). Moreover, policy scenarios can be simulated either with exogenous regulations that imply endogenous demand adjustments or with exogenous demand targets endogenously defining regulatory levels (Lefèvre *et al* 2018).

### 3.4. GLG linkages: responses and feedbacks in LUCC studies

Table 1 summarizes the key papers in our systematic review that study the global feedbacks of local responses to local stressors initiated by drivers of global change discussed in the previous section. An increasing number of theoretical and empirical studies consider bi-directional connections or 'telecoupling' between remote regions (Liu *et al* 2013). Telecoupling exists when market or non-market linkages between regions translate interventions or shocks in one region into corresponding changes in another. In seminal work, (Yu *et al* 2013) estimated 33%, 50%, and 92% of the total land use for consumption in US, EU, and Japan to be displaced from other (developing) countries, respectively. In contrast, agricultural lands in Brazil (47%) and Argentina (88%) are estimated to be driven by consumption demands outside of their territories, mainly in EU and China. Moreover, the same authors highlight that highly-populated emerging economies like China and India are likely to continue increasing land demands, which are expected to be met by African and Latin American countries, and Russia. Similarly, Yao *et al* (2018) applied a telecoupling framework to analyze the economic and environmental consequences of the Brazilian soy boom. They found the Chinese macroeconomic growth to have boosted soybean production and exports from Brazil and the US. Soy productivity growth and the associated area expansion in Brazil were also associated with a loss of US soy market share in the Chinese market and reducing soy production growth in the US. Telecoupling can also affect domestic patterns of LUCC. For example, da Silva *et al* (2017) demonstrate how the increase in international soy trade between Brazil and China led to changes in the Brazilian maize production.

As a result of telecoupling, national or subnational interventions to promote sustainable land use or conservation may have unintended and indirect spillover effects within and across countries, depending on regional and international trade linkages (Meyfroidt *et al* 2013). A well-studied example of such local (national) to global LUCC effects is the impact of US and EU biofuel policies on other crop producing world regions (Garcia and You 2018, Somé *et al* 2018). These policies represent national responses to expected climate change-related stressors and looming fossil fuel scarcity. The renewed impetus of US and EU biofuel policies in the wake of oil price rises after 2006 sharply focused attention on the nature of the market teleconnections leading to LUCC leakage (Searchinger *et al* 2008). Searchinger *et al* (2008) used a PE model of the world economy based on integrated global markets for agricultural commodities (i.e. the law of one price). Simulations suggested that countries with larger areas (China, India, and Brazil) would have the largest cropland responses as a consequence of the US biofuels program, regardless of their exposure to international markets. However, when subjected to statistical testing, the integrated markets hypothesis has been rejected by Villoria and Hertel (2011). They find

that bilateral trade flows do not change as rapidly as would be the case with a unified global market for commodities. This has important implications for the geographic transmission of local interventions across the globe.

Armington (1969) recognized that the relative stability of bilateral trade flows could be captured in a framework in which products are differentiated by their country of origin. Empirical evidence suggests that even relatively homogeneous products such as rice and wheat display markedly rigid patterns of international trade (Hillberry *et al* 2005). These rigid patterns of trade result in segmented markets wherein supply responses to distant shocks depend on the intensity of competition between trading partners in specific markets. Considerations of market segmentation led to more moderate estimates of global GHG emissions from LUCC, although these still largely offset the benefits from domestic reductions (Hertel *et al* 2010b). Based on a similar model simulation, Mosnier *et al* (2013) projected, that the US renewable fuel standard and various alternative policy designs would induce LUCC mainly in Latin America and South-East Asia, largely offsetting US emission reductions. Similar findings were reported in modeling studies for EU biofuel mandates (Al-Riffai *et al* 2010, Britz and Hertel 2009).

Local-to-global interactions are also crucial to explain LUCC due to technological progress in agriculture, but have been somewhat less studied than global-to-local linkages. Even though the role of technology in achieving a more sustainable global food system is widely cited (Godfray *et al* 2010, Tilman *et al* 2011), technological progress can also increase the returns to farming, thereby leading to agricultural expansion, as suggested by 'Jevons paradox' (Alcott 2005). As demonstrated theoretically and via model simulation by Hertel, Ramankutty, and Baldos (Hertel *et al* 2014), this seemingly paradoxical situation depends in part on the observer's point of view. Globally, food demand is highly inelastic (Muhammad *et al* 2011), so better technologies, as captured by growth in overall productivity, are likely to result in global land savings. However, for farmers in a single country that is well-integrated into world markets, local demand is likely quite price-elastic, due to the potential to displace other producers with lower-cost products. Thus, access to better technology tends to encourage local cropland expansion and, potentially, the conversion of native vegetation (Angelsen and Kaimowitz 2001). Indeed, Villoria (2019) finds that, in most countries of the world, productivity growth is either uncorrelated or is positively associated with cropland expansion. However, when one adopts a global perspective, the expansion in the innovating region is likely to displace production elsewhere in the world. Depending on relative yields and emissions factors, these distant reductions—in the form of land abandonment and avoided deforestation—may offset the local increases due to LUCC in the innovating region, thereby leading to global land savings.

Recent studies also reported how productivity growth may spillover across countries and continents. Gasparri *et al* (2016), for example, documented public and private sector linkages that indicate innovation-induced telecoupling between Southern African and South American agricultural frontiers. In South America, the emergence of genetically modified soy varieties has been an enabling factor in the expansion of soy production in the Amazon and the Dry Chaco biomes (Bindraban *et al* 2009, Goldfarb and Zoomers 2013, Leguizamón 2014). The transfer of knowledge and capital accumulated in the South American frontier development may thus accelerate Southern African frontier expansion with associated social costs and benefits that still need to be systematically assessed (Gasparri *et al* 2016).

Our review of selected local-to-global linkages illustrates the various mechanisms at play when we observe linkages between LUCC in spatially separate locations (table 1). First, shocks or interventions arise in individual countries or regions; if sufficiently large to affect aggregate global supply, land use/cover can change in other regions through changes in global commodity prices. Secondly, beyond this price mechanism, spatially distant LUCC impacts of local interventions can be induced by cross-border and international flows of capital, people, knowledge, and technology. Thirdly, the time-dependent innovation process leading to agricultural productivity growth and land use change remains an important research topic. While this may save land globally, it is not immediately clear whether such productivity growth will benefit ecologically sensitive and globally valued ecosystems. An important knowledge gap, therefore, is whether—and to what extent—the land saving effects of agricultural productivity growth have historically contributed to the conservation of native biomes at global scale. The answer clearly depends on where on the planet global mass of cropland contracts and expands over time. In principle, cropland abandonment is less desirable, from a conservation perspective, than avoided expansion into natural ecosystems. Linking biofuel demand and technological change to spatially-explicit LUCC patterns and their drivers at national scale could provide geographically more accurate estimates of such of the local impacts of such drivers of LUCC (Wright *et al* 2017).

National governments under pressure from local stressors, including violent land conflicts at agricultural frontiers or loss of ecosystem services provided by native vegetation, often resort to land-use and conservation policy instruments. The possibility of regional and transnational LUCC leakage induced by such interventions has been demonstrated over a decade ago in simulation exercises (Sohngen and Brown 2004). More recently, empirical evidence related local to global linkages is emerging in the South

American context. In 2004, Brazil initiated a major forest governance reform (e.g. intensification of forest monitoring and law enforcement, land tenure regularization, rural credit access restrictions, and promotion of zero-deforestation supply chains), which has allegedly reduced Amazon forest loss by over 70% (Assunção *et al* 2015, Börner *et al* 2015). Evidence of cross-border leakage induced by this and other regulatory efforts in the region was put forward by le Polain de Waroux *et al* (le Polain de Waroux *et al* 2016), who showed that corporate investment decisions were affected by environmental policy regulation and enforcement. However, a follow-up empirical analysis of regional LUCC patterns could not robustly corroborate causal relationships between alterations in *de jure* land-use restrictions in one country and agricultural expansion in others (le Polain de Waroux et al 2017). Others have also reported similar displacement effects within and among Chaco countries to have contributed to forest loss in the region (Fehlenberg *et al* 2017). Clearer evidence for cross-border leakage in the Guiana Shield was recently reported by Dezecache *et al* (2017), who show that military action to suppress illegal gold-mining and related deforestation in French Guiana led to comparatively large additional forest losses in Suriname.

### 3.5. GLG linkages in LUCC studies: barriers, gaps, and the course ahead

In the previous sections, we explored how GLG-linkages can produce unanticipated LUCC outcomes that involve complex interactions and leakage effects from market and non-market mechanisms. Before we discuss potentially useful approaches to incorporating related features in global simulation or statistical models and fine-scale LUCC analyses, we should emphasize that empirical knowledge of the functioning and strength of these mechanisms is still limited (Baylis *et al* 2016). Causal inference is inherently difficult in analyses of spatially separated cause-effect relationships, i.e. when local interventions produce outcomes in telecoupled regions. Often, no credible counterfactual outcome can be established in standard quasi-experimental studies, because outcomes materialize in units of observations with very different characteristics than those in treatment locations. Empirical work must thus increasingly rely on structural models, new (and big) data sources, and methodological innovations, e.g. synthetic control approaches, based LUCC data with high temporal and spatial resolution (Börner *et al* 2016). Moreover, such studies are paramount to corroborating underlying assumptions and relationships in global agro-economic and other simulation models used to investigate GLG-LUCC linkages.

#### *3.5.1. Summary functions: a bridge from local to global across LUCC models*

One response to the need for capturing endogenous global responses to local land-use policies has been to create *summary functions* which embody all of the economically relevant information about local or regional responses to global changes and which could be directly embedded into the global model. Summary functions (sometimes dubbed *transfer functions*) are widely used to summarize complex biophysical properties which cannot be incorporated into more aggregate models. One example is the rate of nitrate leaching resulting from the application of nitrogen fertilizer in crop production. It is well known that the leaching rate depends on a variety of highly localized factors, such as fertilizer application rate and timing, crop choice, management practices (including cover crops and irrigation), soils, drainage management, and weather, among other things (Kucharik and Brye 2003). Incorporating all of these factors into a national or global gridded model seems nearly impossible. However, by independently estimating grid cell-specific transfer functions and incorporating them into a gridded economic model, it is possible to incorporate grid cell-specific transfer functions. The ensuing model can then be used to explore LUCC leakage effects of non-point source pollution policies at the grid cell level (Liu *et al* 2018).

Britz and Hertel (2009) developed a summary function to provide the linkage between the highly disaggregated CAPRI model (operating at the level of 250 sub-regions) for EU agriculture and the global GTAP-AEZ model. They did so by estimating a system of supply functions which described the aggregate responses of EU agriculture to price changes, as embodied in the CAPRI model. This permitted them to estimate the global land use impacts of EU-based biofuel policies. In later work, the same authors extended this summary function approach to incorporate a specific, land-based policy lever—in this case, an index of the stringency of the EU agricultural land set-aside program. This allowed them to simulate the spillover effects of this very specific EU-land use policy in a global model, and then link the EU market price results back to the disaggregated CAPRI model in order to assess the detailed effects of this intervention at the regional level (Pelikan *et al* 2014). Summary functions have also been used to represent land use change in hydrological models (Hundecha and Bárdossy 2004). However, the estimation of internally consistent summary functions is a non-trivial task. For example, Britz and Hertel (2009) were able to exploit the fact that the CAPRI model adheres to well-understood theoretical economic properties, which may not be the case with other models.

Just as summary functions can be used as a bridge from local to global analyses, so, too, can they be used as a means of incorporating a summary of key global

responses into local analyses of LUCC and leakage. This could allow for better harmonization and interpretation of cross-model simulations (Schmitz *et al* 2014, von Lampe *et al* 2014, Alexander *et al* 2017, Popp *et al* 2017). Such summaries of composite economic responses can also allow for rapid insights into the potential impacts of local LUCC in response to various interventions. Consider, for example, local assessments of the impacts of agricultural technology improvements. Hertel *et al* (2014) demonstrate that, all of the relevant information about global demand for the commodity in question, as well as supply response in the rest of the world, is embodied in one parameter—the price elasticity of excess demand. If the value of this parameter is greater than one, then economic theory predicts that cropland will expand in response to the technological innovation, otherwise, land use will contract. The value of this parameter can be readily estimated from any global model, simply by perturbing the local supply function and observing the ensuing change in equilibrium quantity and price. Researchers focusing on local LUCC should consider eliciting this excess demand elasticity from appropriately configured global models (Plevin *et al* 2015), thereby allowing them to leverage the relevant global information without having to run the global model repeatedly.

*3.5.2. Model validation: the 'Holy Grail'*

In the context of GLG-LUCC linkages, we find that the question of model validity is rarely explored in global models. In particular, we found that global agro-economic model validity tends to deteriorate as models become more complex and more disaggregated (McCalla and Revoredo 2001). This is unfortunate given the perceived demand for additional disaggregation in the LUCC literature.

Validation is a critical piece of the puzzle if global simulation models are to have broader relevance for science and policy. Two types of validation have been undertaken with global agro-economic models: *ex post* validation and historical validation (or hindcasting). *Ex post* validation, i.e. comparing model predictions with actual outcomes realized at a later date, is rarely practiced. A notable exception is McCalla and Revoredo (2001), who evaluate how actual outcomes deviated from the modeling teams' earlier projections of global food output. Based on their analysis, the FAO projections improved over time for wheat but were less accurate for oilseeds, which grew dramatically over this period. This contrasts sharply with their assessment of the global commodity projections made by IFPRI and USDA over this period. The deviations of these agencies' predictions from actual outcomes grew over time. The authors argued this was due to the demands for greater regional disaggregation. Indeed, their review suggests that forecast errors were larger, the smaller the economy—often due to low-quality data. In addition, they found evidence of large projections errors for the US and EU where changing agricultural policies exerted an inordinate influence. The authors concluded their review by suggesting it is difficult for global models to reach clear conclusions about the evolution of agricultural production and consumption in specific countries. Their findings pose a challenge for those undertaking global gridded modeling, where the objective is to project outcomes for highly resolved subnational regions.

Historical validation or 'hindcasting,' the second and most common approach to the validation challenge in global modeling, relies on the comparison of simulated outputs to historical 'real-world' data. This method has become standard in climate modeling (Oreskes *et al* 1994, Brands *et al* 2013), but there are relatively few recent examples of historical validation of agro-economic models (Schmitz *et al* 2012, Chen and Khanna 2018, Soterroni *et al* 2018, Yao *et al* 2018). One notable example is offered by Dietrich *et al* (2014) who ran the MAgPIE model over the period 1995–2060 and examined productivity changes at the continental scale, comparing predictions to historical observations over the decade from 1995 to 2005. Their model predictions fit well in some regions but depended heavily on the assumptions about forest conservation policies.

The reportedly limited experience with model validation also suggests that much more attention needs to be paid to the land-use/cover data being used in these models, as well as the estimation of key behavioral parameters in LUCC models (Filatova *et al* 2013). This includes the price and income responsiveness of food demand, the potential for endogenous intensification of crop production, the responsiveness of cropland area to economic signals, and the extent of integration with international commodity markets. For example, Verburg and Overmars (2009) highlight the fact that land-cover databases such as the 1990 and 2000 CORINE European land-cover maps do not effectively distinguish between recently abandoned farmland and grassland or identify alternative land uses of former agricultural areas. Moreover, Alexander *et al* (2017) suggested that the greater research efforts placed on the roles of cropland and European land led to greater consistency among multiple models' simulations due to lower variance in initial areas. Many models also derive forest area change from changes in cropland, without consideration for potential demands for forest products or non-market ecosystem services (Schmitz *et al* 2014). With less attention paid to other land types in global economic models, agricultural areas may inadequately account for the interactions between demands for other uses, e.g. timber (Alexander *et al* 2017).

*3.5.3. Gridded data and parameters: a critical limitation*

It is difficult to overstate the importance of accurate, detailed data on crops and related land-use practices (e.g. irrigation and fertilization) for high-resolution

global-level modeling efforts. The pioneering work of Monfreda *et al* (2008), though anchored nearly two decades ago, circa 2000, still remains one of the most frequently used data products for the global spatial distribution of harvested areas and yields[8] (175 FAO crops). Another key piece of information for GLG-LUCC analysis is the spatial location of cropland, pastures, and natural land covers such as forests and grasslands. Land-cover products based on automated processing of satellite data are relatively current (e.g. *GlobCover* from the *European Spatial Agency* updated to 2010), but they tend to underestimate the cropland statistics compiled from FAO (Fritz *et al* 2013). A recent land-cover dataset from NASA that is representative of 2015, in contrast, identified 15%–20% more cropland than formerly assessed (Congalton *et al* 2017). Alternative datasets that are cropland specific are representative of land use in the first decade of the 2000s (Goldewijk 2001, Klein Goldewijk *et al* 2007, Ramankutty *et al* 2008, Fritz *et al* 2015). We still lack globally consistent data on other key aspects related to land use such as labor allocation, the location of processing plants (e.g. bio-refineries) and the distribution of agricultural input and output prices. Exceptions are the global map on fertilizer application (Potter *et al* 2010) and irrigation maps (Siebert *et al* 2010), both representative of the early 2000s.

An obstacle to improving the globally gridded data available to researchers is the generalized perception that the data offered by international organizations, combined with the increasing availability of data and computing capabilities for data processing and visualization, automatically translates into impressive maps and state-of-the-art datasets that can improve GLG-LUCC analysis. As evidenced by the short discussion above, this is simply not the case. Given the advances in satellite imagery processing and the experiences mapping national and subnational information, the time seems ripe for a globally coordinated effort geared toward the continuous improvement of the data needed by the scientific community. As discussed by Fritz *et al* (2013), better algorithms to process global moderate resolution satellite data are a promising solution for annually updated cropland maps, although considerable methodological refinements are needed to make these maps accurate. One methodological refinement is in the recent work of Graesser *et al* (2015) which shows that the interpretation of moderate-resolution satellite data can be significantly improved by validation through sampling and expert interpretation of the high-resolution imagery offered by Google Earth. Another is the use of machine learning to identify patterns of burning and plantation establishment in Indonesia (Jia *et al* 2016).

Regarding crop level information, Lobell (2013) and Burke and Lobell (2017) have shown that satellite imagery can be used to infer yields and yield gaps. The data fusion methods of Monfreda *et al* (2008), whereby land-cover information from satellite imagery is combined with detailed data on agricultural area and production from national censuses with subnational information, could be enhanced and automated so new information can be digested and incorporated, shortening the time span between data updates. New research using simple discrete-choice regression techniques for downscaling subnational data seems a promising area of endeavor (Song *et al* 2018). The experiences with crowdsourcing from See *et al* (2015) offers a glimpse into how to collaborate with the broader community to validate and improve the cropland and other maps over time.

The root cause of the lack of improvement in the global gridded datasets over time, despite increasing availability of satellite data, is the fact that most of these efforts are based on one-time academic and institutional projects, which quickly become outdated and lack inter-operability (Hertel *et al* 2010a). This is a consequence of several factors. Firstly, the incentives for the development and maintenance of data sets in academia are quite limited. Even those authors who have garnered widespread citations for published data sets do not have a strong incentive to update them. In addition, these data sets often entail collaboration across disciplines (e.g. agronomy, hydrology, climate science, geography and economics), further increasing the challenge for many academics. The provision of such public goods is the natural domain of governmental bodies. However, this is expensive and cutting data collection and maintenance is often one of the first ways agencies come to grips with budget reductions. Given the skill-specific nature of global gridded data, once a team is disbanded, it is costly to reassemble, and the all-important continuity in time series data is typically lost.

While competing approaches are a desirable attribute that allows for new and improved discovery, data users often lack guidance in terms of data product accuracy. An ideal system would involve a research environment that produces updated data, with protocols that can ensure consistency across research groups and a vetting system that can guide users to select the best datasets while encouraging ongoing improvements (Hertel *et al* 2010a).

A related concern is the lack of parameter estimates that regulate economic behavior in LUCC models. For instance, the elasticities of factor supplies (i.e. land, labor, and agriculture) are among the most important parameters explaining LUCC in the recent past (David *et al* 2013, Baldos and Hertel 2016). These

[8] To the best of our knowledge, the only alternative to Monfreda *et al* (2008)'s datasets are the yield and harvested area maps underlying the Global Agroecological Zones Model (IIASA/FAO 2010). In contrast to Monfreda *et al* (2008), GAEZ downscales country level aggregates, ignoring the distributional information contained in subnational statistics. Moreover, the GAEZ data is for 23 commodities only, as opposed to the 175 crops in Monfreda *et al* (2008). As with that product, GAEZ estimates are representative of year 2000.

are also the parameters about which we know the least, and what is known comes from efforts three or four decades ago, generally focusing in the developed world. Parameter estimation does not necessarily depend on the availability of spatially explicit data, but when these data are available, the understanding of many phenomena is greatly enhanced. For example, Lubowski (2002) exploits the spatially-explicit LUCC information (e.g. cropland, forest, range, and pastures) in the *US Crop Data Layer* to estimate LUCC transition elasticities in the US; these elasticities underpin most of the global-to-local analysis based on the GTAP-AEZ framework (Ahmed *et al* 2008). Their results predict LUCC reasonably correlated with observed changes across the continental US while identifying opportunities to increase estimation accuracy by incorporating data about the location of biorefineries and other processing facilities. In contrast, many global agro-economic models deriving LUCC from changes in agricultural areas (Schmitz *et al* 2014) often disregard the key roles of biophysical attributes (e.g. distance to roads, slope, and soil and climate suitability) well-known to be strongly correlated with agricultural land uses (Busch and Ferretti-Gallon 2017, Kleemann *et al* 2017, Restivo *et al* 2018).

Even if spatially-explicit data does not allow for parameter estimation, it can be used to spatialize existing country-level parameters. For example, Villoria and Liu (2018) used data on biophysical attributes and global market access maps prepared by Verburg *et al* (2011) to estimate land supply elasticities at the grid-cell level—the land supply elasticity in this context is the percentage change in cropland area given a one percent change in agricultural rents. This parameter is crucial in LUCC modeling because it determines the extensive margin of the supply response to changes in the expected profitability of agricultural production. In addition to land quality, transport costs to markets are key determinants of these supply elasticities. Transport costs, in turn, vary with relative prices and can be substantially modified by investments in infrastructure such as roads (Chomitz and Gray 1996) or biorefineries (Li *et al* 2019). The combination of maps of market access with well-established econometric models of land use choice allows to capture the effects of investments in reducing transportation costs (Chomitz and Gray 1996), which are a key determinant of deforestation and cropland expansion (Pfaff 1999, Laurance *et al* 2014). This further underscores the need to intensify collaboration between economists, biophysical scientists, and geographers.

## 4. Summary and future research directions

While there is a great deal of important work underway in GLG-LUCC modeling, most current approaches fall prey to one or more of the following three key limitations. The first of these is that many studies remain a prisoner of an *excessive disciplinary orientation*. LUCC science specifically, and the sustainability challenges facing the world today more generally, are fundamentally interdisciplinary in nature. Approaches driven solely by geographers, agronomists, ecologists or economists will ultimately prove too narrow in their analyses. This interdisciplinary thrust is evident from the LUCC work currently being undertaken at the large international institutions. However, we believe that future GLG-LUCC analyses and leakage will benefit from even greater interdisciplinary collaboration, particularly on the part of individual academic researchers working in this field.

A second limitation of much of the work to date on GLG-LUCC and leakage, as reflected in this review, is that most of the work focuses on the global-to-local component, with far fewer studies characterizing the local-to-global linkages. As mentioned above, by their very nature, land-based sustainability challenges usually require local solutions, with the preferred approach depending on current use, soil characteristics, topography, access to water and agricultural inputs, infrastructure, as well as socio-economic conditions and governance. However, local analyses, disconnected from national and global contexts, cannot foresee future system stresses nor can they anticipate the spillovers and broader consequences of local solutions (Rounsevell *et al* 2012).

Where the full GLG-LUCC nexus has been developed, as with the global gridded modeling projects discussed above, we observe an excessive reliance on *proprietary and complex analysis frameworks*. It is hardly surprising that this kind of major undertaking has typically been undertaken in large national and international institutions. However, most of these modeling frameworks have been proprietary in nature. While there are currently significant efforts underway to make several of the leading integrated assessment models open-source (e.g. GCAM and MAgPIE), it is hard to get serious uptake due to the complexity of the underlying modeling frameworks that are often not well documented and are being continually expanded to address new challenges and new projects. It is hard to think of any example where outsiders have been able to effectively use and modify these global gridded modeling frameworks. If one is to build a community of practice around GLG-LUCC analyses, the underlying models and data should be open-source and developed from the very beginning with the premise that they will be used by a variety of individuals, from various institutions, with differing backgrounds and skill levels. This calls for a suite of models that are simple enough to be accessible to a wide range of users, while not being so simple that they abstract from key issues underpinning global LUCC and leakage. Open-sourcing will also permit more ground-truthing of local data and behavioral assumptions. One open-source source effort known as *Global to Local Analysis of Systems Sustainability* seeks to

provide researchers with the entire workflow behind GLG-LUCC analyses—starting with the data and parameters underlying the open-source models provided on the *GeoHub* (https://mygeohub.org/groups/glass). This type of project is complementary to efforts to foster a global community working on sustainable land use in a global context, of which the *Global Land Program* (https://glp.earth/) is the most prominent example. It is only through such collaboration that the 'wicked problems' posed by GLG-LUCC and leakage in the 21st century can be adequately addressed.

## Acknowledgments

This research has been funded by the German Federal Ministry of Education and Research (BMBF) as part of the project STRIVE (Sustainable Trade and Innovation Transfer in the Bioeconomy), the German Federal Ministry for Economic Cooperation and Development (BMZ), and the Robert Bosch Foundation. We thank the participants at the workshop 'Land use spillover and leakage effects: towards integrating concepts, empirical methods, and models', 9–10 November 2017, at the Robert Bosch Foundation (Berlin), and two anonymous reviewers for valuable comments that have substantially improved the initial version of the manuscript. Hertel acknowledges funding from NSF (SES-1463644), USDA-NIFA (IND01053G2) and Hatch (100342). Villoria acknowledges funding from NSF (#1739253) and USDA-NIFA (#2016-67023-24637 and Hatch/Multistate project # S1072).

## Appendix

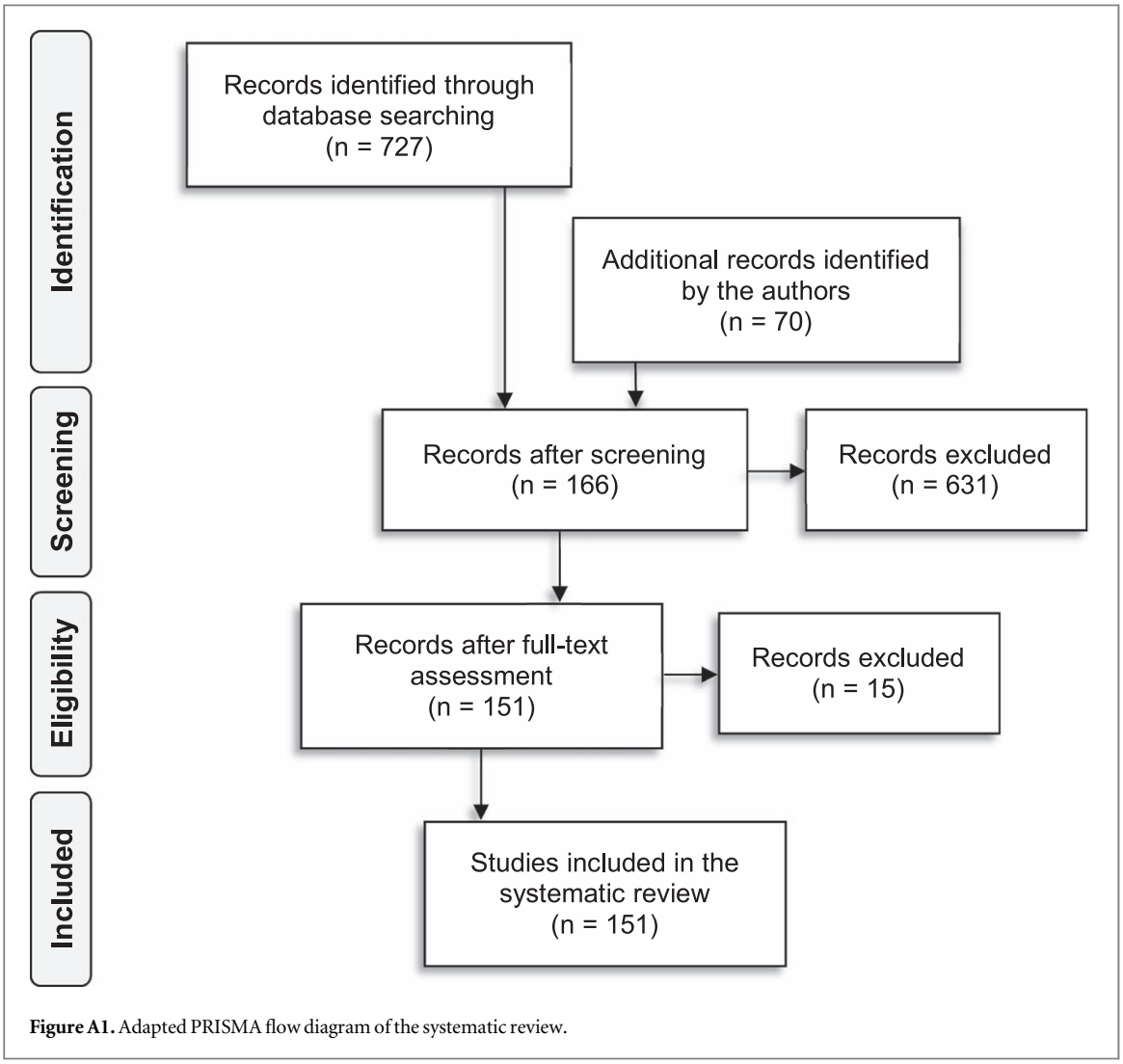


**Figure A1.** Adapted PRISMA flow diagram of the systematic review.

## ORCID iDs

Thomas W Hertel https://orcid.org/0000-0002-7179-7630
Thales A P West https://orcid.org/0000-0003-3896-6516
Nelson B Villoria https://orcid.org/0000-0003-3034-5360

## References

Ahmed S A, Hertel T W and Lubowski R 2008 Calibration of a land cover supply function using transition probabilities *GTAP Research Memorandum No 14* Department of Agricultural Economics, Purdue University
Alcott B 2005 Jevons' paradox *Ecol. Econ.* **54** 9–21
Alexander P *et al* 2017 Assessing uncertainties in land cover projections *Glob. Change Biol.* **23** 767–81
Al-Riffai P, Dimaranan B and Laborde D 2010 *Global Trade and Environmental Impact Study of the EU Biofuels Mandate* (Washington, DC: International Food Policy Research Institute)
Angelsen A and Kaimowitz D 2001 When does technological change in agriculture promote deforestation *Tradeoffs or Synergies? Agricultural Intensification, Economic Development and the Environment* ed D R Lee and C B Barrett (Wallingford: CABI Publishing)
Arima E Y, Richards P, Walker R and Caldas M M 2011 Statistical confirmation of indirect land use change in the Brazilian Amazon *Environ. Res. Lett.* **6** 24010
Armington P S 1969 A theory of demand for products distinguished by place of production *Staff Pap. (Int. Monet. Fund)* **16** 159–78
Assunção J, Gandour C and Rocha R 2015 Deforestation slowdown in the Brazilian Amazon: prices or policies? *Environ. Dev. Econ.* **20** 697–722
Baldos U L C and Hertel T W 2016 Debunking the 'new normal': why world food prices are expected to resume their long run downward trend *Glob. Food Secur.* **8** 27–38
Barona E, Ramankutty N, Hyman G and Coomes O T 2010 The role of pasture and soybean in deforestation of the Brazilian Amazon *Environ. Res. Lett.* **5** 24002
Baylis K, Honey-Rosés J, Börner J, Corbera E, Ezzine-de-Blas D, Ferraro P J, Lapeyre R, Persson U M, Pfaff A and Wunder S 2016 Mainstreaming impact evaluation in nature conservation *Conservation Lett.* **9** 58–64
Bindraban P S, Bulte E H and Conijn S G 2009 Can large-scale biofuels production be sustainable by 2020? *Agric. Syst.* **101** 197–9
Blatt A J 2015 *Health, Science, and Place: A New Model* (Berlin: Springer)
Bondeau A *et al* 2007 Modelling the role of agriculture for the 20th century global terrestrial carbon balance *Glob. Change Biol.* **13** 679–706
Brands S, Herrera S, Fernández J and Gutiérrez J M 2013 How well do CMIP5 earth system models simulate present climate conditions in Europe and Africa? A performance comparison for the downscaling community *Clim. Dyn.* **41** 803–17
Britz W and Hertel T W 2009 Impacts of EU biofuels directives on global markets and EU environmental quality: an integrated PE, global CGE analysis *Agric. Ecosyst. Environ.* **142** 102–9
Burke M and Lobell D B 2017 Satellite-based assessment of yield variation and its determinants in smallholder African systems *Proc. Natl Acad. Sci.* **114** 2189–94
Busch J and Ferretti-Gallon K 2017 What drives deforestation and what stops it? A meta-analysis *Rev. Environ. Econ. Policy* **11** 3–23
Börner J, Baylis K, Corbera E, Ezzine-de-Blas D, Ferraro P J, Honey-Rosés J, Lapeyre R, Persson U M and Wunder S 2016 Emerging evidence on the effectiveness of tropical forest conservation *PLoS One* **11** e0159152
Börner J, Kis-Katos K, Hargrave J and König K 2015 Post-crackdown effectiveness of field-based forest law enforcement in the Brazilian Amazon *PLoS One* **10** 1–19
Calvin K, Wise M, Clarke L, Edmonds J, Kyle P, Luckow P and Thomson A 2013 Implications of simultaneously mitigating and adapting to climate change: initial experiments using GCAM *Clim. Change* **117** 545–60
Chatterjee N, Nair P K R, Chakraborty S and Nair V D 2018 Changes in soil carbon stocks across the forest-agroforest-agriculture/pasture continuum in various agroecological regions: a meta-analysis *Agric. Ecosyst. Environ.* **266** 55–67
Chen X and Khanna M 2018 Effect of corn ethanol production on Conservation Reserve Program acres in the US *Appl. Energy* **225** 124–34
Chomitz K M and Gray D A 1996 Roads, land use, and deforestation: a spatial model applied to belize *World Bank Econ. Rev.* **10** 487–512
Cohn A S, Mosnier A, Havlik P, Valin H, Herrero M, Schmid E, O'Hare M and Obersteiner M 2014 Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation *Proc. Natl Acad. Sci.* **111** 7236–41
Congalton R G, Yadav K, McDonnell K, Poehnelt J, Stevens B, Gumma M K, Teluguntla P and Thenkabail P S 2017 NASA making earth system data records for use in research environments (MEaSUREs) global food security-support analysis Data (GFSAD) Cropland Extent 2015 Validation Global 30 m V001 (https://earthdata.nasa.gov/community/community-data-system-programs/measures-projects)
Curtis P G, Slay C M, Harris N L, Tyukavina A and Hansen M C 2018 Classifying drivers of global forest loss *Science* **361** 1108–11
da Silva R F B, Batistella M, Dou Y, Moran E, Torres S M and Liu J 2017 The Sino-Brazilian telecoupled soybean system and cascading effects for the exporting country *Land* **6** 53
Darwin R, Tsigas M, Lewandrowski J and Raneses A 1995 *World Agriculture and Climate Change: Economic Adaptations* (Washington, DC: Natural Resources and Environment Division, Economic Research Service, US Department of Agriculture)
David B L, Uris Lantz C B and Thomas W H 2013 Climate adaptation as mitigation: the case of agricultural investments *Environ. Res. Lett.* **8** 15012
Delzeit R, Klepper G, Zabel F and Mauser W 2018 Global economic-biophysical assessment of midterm scenarios for agricultural markets—biofuel policies, dietary patterns, cropland expansion, and productivity growth *Environ. Res. Lett.* **13** 025003
Dezecache C, Faure E, Gond V, Salles J-M, Vieilledent G and Hérault B 2017 Gold-rush in a forested El Dorado *Environ. Res. Lett.* **12** 34013
Dietrich J P, Schmitz C, Lotze-Campen H, Popp A and Müller C 2014 Forecasting technological change in agriculture—an endogenous implementation in a global land use model *Technol. Forecast. Soc. Change* **81** 236–49
Doelman J C *et al* 2018 Exploring SSP land-use dynamics using the IMAGE model: regional and gridded scenarios of land-use change and land-based climate change mitigation *Glob. Environ. Change* **48** 119–35
FAO 1962 *The State of Food and Agriculture 1962* (Rome: Food and Agriculture Organization of the United Nations)
Fehlenberg V, Baumann M, Gasparri N I, Piquer-Rodriguez M, Gavier-Pizarro G and Kuemmerle T 2017 The role of soybean production as an underlying driver of deforestation in the South American Chaco *Glob. Environ. Change* **45** 24–34
Filatova T, Verburg P H, Parker D C and Stannard C A 2013 Spatial agent-based models for socio-ecological systems: challenges and prospects *Environ. Model. Softw.* **45** 1–7
Fischer G and Frohberg K 1982 The basic linked system of the food and agriculture program at IIASA: an overview of the structure of the national models *Math. Model.* **3** 453–66
Frank S, Böttcher H, Gusti M, Havlík P, Klaassen G, Kindermann G and Obersteiner M 2016 Dynamics of the

land use, land use change, and forestry sink in the European Union: the impacts of energy and climate targets for 2030 *Clim. Change* **138** 253–66
Fritz S *et al* 2013 The need for improved maps of global cropland *Eos, Trans. Am. Geophys. Union* **94** 31–2
Fritz S *et al* 2015 Mapping global cropland and field size *Glob. Change Biol.* **21** 1980–92
Fujimori S, Hasegawa T, Masui T, Takahashi K, Herran D S, Dai H, Hijioka Y and Kainuma M 2017 SSP3: AIM implementation of shared socioeconomic *Pathways Glob. Environ. Change* **42** 268–83
Garcia D J and You F 2018 Addressing global environmental impacts including land use change in life cycle optimization: studies on biofuels *J. Clean. Prod.* **182** 313–30
Gasparri N I, Kuemmerle T, Meyfroidt P, le Polain de Waroux Y and Kreft H 2016 The emerging soybean production frontier in southern Africa: conservation challenges and the role of South–South telecouplings *Conservation Lett.* **9** 21–31
Godfray H C J, Beddington J R, Crute I R, Haddad L, Lawrence D, Muir J F, Pretty J, Robinson S, Thomas S M and Toulmin C 2010 Food security: the challenge of feeding 9 billion *People Sci.* **327** 812–8
Godfray H C J and Garnett T 2014 Food security and sustainable intensification *Phil. Trans. R. Soc.* B **369** 20120273
Goldewijk K K 2001 Estimating global land use change over the past 300 years: the HYDE database *Glob. Biogeochem. Cycles* **15** 417–33
Goldfarb L and Zoomers A 2013 The drivers behind the rapid expansion of genetically modified soya production into the Chaco region of Argentina *Biofuels—Economy, Environment and Sustainability* ed Z Fang (Rijeka: InTech)
Graesser J, Aide T M, Grau H R and Ramankutty N 2015 Cropland/pastureland dynamics and the slowdown of deforestation in Latin America *Environ. Res. Lett.* **10** 34017
Havlik P 2015 Climate change impacts and mitigation in the developing world: an integrated assessment of the agriculture and forestry sectors *Policy Research Working Paper No.* 7477 (Washington, DC: World Bank)
Havlik P *et al* 2014 Climate change mitigation through livestock system transitions *Proc. Natl Acad. Sci.* **111** 3709–14
Havlik P, Valin H, Mosnier A, Obersteiner M, Baker J S, Herrero M, Rufino M C and Schmid E 2013 Crop productivity and the global livestock sector: implications for land use change and greenhouse gas emissions *Am. J. Agric. Econ.* **95** 442–8
Hertel T W (ed) 1997 *Global Trade Analysis: Modeling and Applications* (New York: Cambridge University Press)
Hertel T W, Baldos U L C and van der Mensbrugghe D 2016 Predicting long-term food demand, cropland use, and prices *Annu. Rev. Resour. Econ.* **8** 417–41
Hertel T W, Britz W, Diffenbaugh N S, Ramankutty N and Villoria N 2010a *A Global, Spatially Explicit, Open Source Data Base for Analysis of Agriculture, Forestry, and the Environment: Proposal and Institutional Considerations* (West Lafayette: Purdue University)
Hertel T W, Golub A A, Jones A D, O'Hare M, Plevin R J and Kammen D M 2010b Effects of US maize ethanol on global land use and greenhouse gas emissions: estimating market-mediated responses *Bioscience* **60** 223–31
Hertel T W, Ramankutty N and Baldos U L C 2014 Global market integration increases likelihood that a future African Green Revolution could increase crop land use and $CO_2$ emissions *Proc. Natl Acad. Sci.* **111** 13799–804
Hertel T W, Rose S and Tol R S J 2009 *Economic Analysis of Land Use in Global Climate Change Policy* (New York: Routledge)
Hillberry R H, Anderson M A, Balistreri E J and Fox A K 2005 Taste parameters as model residuals: assessing the 'fit' of an Armington trade model *Rev. Int. Econ.* **13** 973–84
Hundecha Y and Bárdossy A 2004 Modeling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model *J. Hydrol.* **292** 281–95
Hunter L M, Luna J K and Norton R M 2015 Environmental dimensions of migration *Annual Rev. of Sociol.* **41** 377–97
Hurtt G C *et al* 2011 Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands *Clim. Change* **109** 117–61
IIASA/FAO 2010 GAEZ 2009. Global Agro-ecological Zones. Model Documentation. GAEZ 3.0
Intergovernmental Panel on Climate Change (IPCC) 2014 *Climate Change 2013—The Physical Science Basis* ed T F Stocker (Cambridge: Cambridge University Press)
Jia X, Khandelwal A, Gerber J, Carlson K, West P C, Samberg L and Kumar V 2016 Learning large-scale plantation mapping from imperfect annotators *2016 IEEE Int. Conf. on Big Data (Big Data) (Washington, DC)* vol 2016, pp 1192–201
Kleemann J, Baysal G, Bulley H N N and Fürst C 2017 Assessing driving forces of land use and land cover change by a mixed-method approach in north-eastern Ghana, West Africa *J. Environ. Manage.* **196** 411–42
Klein Goldewijk K, Van Drecht G and Bouwman A F 2007 Mapping contemporary global cropland and grassland distributions on a 5 × 5 min resolution *J. Land Use Sci.* **2** 167–90
Kriegler E *et al* 2017 Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century *Glob. Environ. Change* **42** 297–315
Kucharik C J and Brye K R 2003 Integrated biosphere simulator (IBIS) yield and nitrate loss predictions for Wisconsin maize receiving varied amounts of nitrogen fertilizer *J. Environ. Qual.* **32** 247
Laborde D and Valin H 2012 Modeling land-use changes in a global CGE: assessing the EU biofuel mandates with the MIRAGE-BioF model *Clim. Change Econ.* **3** 1250017
Lambin E F, Geist H J and Lepers E 2003 Dynamics of land-use and land-cover change in tropical regions *Annu. Rev. Environ. Resour.* **28** 205–41
Lanz B, Dietz S and Swanson T 2018 The expansion of modern agriculture and global biodiversity decline: an integrated assessment *Ecol. Econ.* **144** 260–77
Lapola D M, Schaldach R, Alcamo J, Bondeau A, Koch J, Koelking C and Priess J A 2010 Indirect land-use changes can overcome carbon savings from biofuels in Brazil *Proc. Natl Acad. Sci.* **107** 3388–93
Laurance W F *et al* 2014 A global strategy for road building *Nature* **513** 229–32
Lee H L, Hertel T W, Rose S and Avetsiyan M 2009 An integrated land use data base for CGE analysis of climate policy options *Economic Analysis of Land Use in Global Climate Change Policy* ed S R and R T T W Hertel (New York: Routledge)
Lee J-S, Filatova T, Ligmann-Zielinska A, Hassani-Mahmooei B, Stonedahl F, Lorscheid I, Voinov A, Polhill G, Sun Z and Parker D C 2015 The complexities of agent-based modeling output analysis *J. Artif. Soc. Soc. Simul.* **18** 1–27
Lefèvre J, Wills W and Hourcade J C 2018 Combining low-carbon economic development and oil exploration in Brazil? an energy–economy assessment *Clim. Policy* **18** 1286–95
Leguizamón A 2014 Modifying Argentina: GM soy and socio-environmental change *Geoforum* **53** 149–60
Leimbach M, Bauer N, Baumstark L and Edenhofer O 2010 Mitigation costs in a globalized world: climate policy analysis with REMIND-R *Environ. Model. Assess.* **15** 155–73
le Polain de Waroux Y, Garrett R D, Graesser J, Nolte C, White C and Lambin E F 2017 The restructuring of South American soy and beef production and trade under changing environmental regulations *World Dev.* accepted (https://doi.org/10.1016/j.worlddev.2017.05.034)
le Polain de Waroux Y, Garrett R D, Heilmayr R and Lambin E F 2016 Land-use policies and corporate investments in agriculture in the Gran Chaco and Chiquitano *Proc. Natl Acad. Sci.* **113** 4021–6
Li Y, Miao R and Khanna M 2019 Effects of ethanol plant proximity and crop prices on land-use change in the United States *Am. J. Agric. Econ.* **101** 467–91
Liu J *et al* 2013 Framing sustainability in a telecoupled world *Ecol. Soc.* **18** 26

Liu J, Hertel T, Bowling L, Jame S, Kucharik C and Ramankutty N 2018 Evaluating alternative options for managing nitrogen losses from corn production *Purdue Policy Res. Inst., Policy Brief* **4** 9

Liu J, Hertel T W, Lammers R B, Prusevich A, Baldos U L C, Grogan D S and Frolking S 2017 Achieving sustainable irrigation water withdrawals: global impacts on food security and land use *Environ. Res. Lett.* **12** ed 104009

Lobell D B 2013 The use of satellite data for crop yield gap analysis *Field Crops Res.* **143** 56–64

Lotze-Campen H, Müller C, Bondeau A, Rost S, Popp A and Lucht W 2008 Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach *Agric. Econ.* **39** 325–38

Lubowski R 2002 Determinants of land-use transitions in the United States: econometric analysis of changes among the major land-use categories *PhD Dissertation* Cambridge: Harvard University

Lungarska A and Chakir R 2018 Climate-induced land use change in France: impacts of agricultural adaptation and climate change mitigation *Ecol. Econ.* **147** 134–54

Malthus T R 1798 *An Essay on the Principle of Population* (London: J. Johnson) pp 125

McCalla A F and Revoredo C L 2001 *Prospects for Global Food Security: A Critical Appraisal of Past Projections and Predictions* (Washington DC: International Food Policy Research Institute) 2020 vision Discussion Paper no. 35

Meadows D H, Meadows D L, Randers J and Behrens W 1972 *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind* (New York: Universe Books)

Melillo J M, Reilly J M, Kicklighter D W, Gurgel A C, Cronin T W, Paltsev S, Felzer B S, Wang X, Sokolov A P and Schlosser C A 2009 Indirect emissions from biofuels: how important? *Science* **326** 1397–9

Meyfroidt P, Lambin E F, Erb K-H and Hertel T W 2013 Globalization of land use: distant drivers of land change and geographic displacement of land use *Curr. Opin. Environ. Sustain.* **5** 438–44

Monfreda C, Ramankutty N and Foley J A 2008 Farming the planet: II. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000 *Glob. Biogeochem. Cycles* **22** GB1022

Mosnier A, Havlík P, Valin H, Baker J, Murray B, Feng S, Obersteiner M, McCarl B A, Rose S K and Schneider U A 2013 Alternative US biofuel mandates and global GHG emissions *Energy Policy* **57** 602–614

Muhammad A, Seale J L Jr, Meade B and Regmi A 2011 International evidence on food consumption patterns: an update using 2005 international comparison program data *Technical Bulletin No.* 1929 (Washington, DC: Economic Research Service, US Department of Agriculture)

Murray-Rust D, Brown C, van Vliet J, Alam S J, Robinson D T, Verburg P H and Rounsevell M 2014 Combining agent functional types, capitals and services to model land use dynamics *Environ. Model. Softw.* **59** 187–201

Nelson G C *et al* 2014 Climate change effects on agriculture: economic responses to biophysical shocks *Proc. Natl Acad. Sci.* **111** 3274–3279

Obersteiner M *et al* 2016 Assessing the land resource–food price nexus of the Sustainable Development Goals *Sci. Adv.* **2** e1501499

O'Neill B C, Kriegler E, Riahi K, Ebi K L, Hallegatte S, Carter T R, Mathur R and van Vuuren D P 2014 A new scenario framework for climate change research: the concept of shared socioeconomic pathways *Clim. Change* **122** 387–400

Oreskes N, Shrader-Frechette K and Belitz K 1994 Verification, validation, and confirmation of numerical models in the earth sciences *Science* **263** 641–646

Pelikan J, Britz W and Hertel T W 2014 Green light for green agricultural policies? An analysis at regional and global scales *J. Agric. Econ.* **66** 1–19

Pfaff A S P 1999 What drives deforestation in the brazilian amazon? Evidence from satellite and socioeconomic data *J. Environ. Econ. Manage.* **37** 26–43

Plevin *et al* 2015 Carbon accounting and economic model uncertainty of emissions from biofuels-induced land use change *Environ. Sci. Tech.* **49** 2656–64

Popp A *et al* 2014 Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options *Clim. Change* **123** 495–509

Popp A *et al* 2017 Land-use futures in the shared socio-economic pathways *Glob. Environ. Change* **42** 331–345

Popp A, Lotze-Campen H, Leimbach M, Knopf B, Beringer T, Bauer N and Bodirsky B 2011 On sustainability of bioenergy production: integrating co-emissions from agricultural intensification *Biomass Bioenergy* **35** 4770–4780

Porfirio L L, Newth D, Finnigan J J and Cai Y 2018 Economic shifts in agricultural production and trade due to climate change *Palgrave Commun.* **4** 111

Potter P, Ramankutty N, Bennett E M and Donner S D 2010 Characterizing the spatial patterns of global fertilizer application and manure production *Earth Interact.* **14** 1–22

Ramankutty N, Evan A T, Monfreda C and Foley J A 2008 Farming the planet: I. Geographic distribution of global agricultural lands in the year 2000 *Global Biogeochem. Cycles* **22** GB1003

Reilly J *et al* 2003 US agriculture and climate change: new results *Clim. Change* **57** 43–67

Reilly J, Melillo J, Cai Y, Kicklighter D, Gurgel A, Paltsev S, Cronin T, Sokolov A and Schlosser A 2012 Using land to mitigate climate change: hitting the target, recognizing the trade-offs *Environ. Sci. Technol.* **46** 5672–5679

Restivo M, Shandra J M and Sommer J M 2018 The United States agency for international development and forest loss: a cross-national analysis of environmental aid *Soc. Sci. J.* **55** 171–181

Rojko A 2017 *Alternative Futures for World Food in 1985, Vol. 3: World GOL Model Structure and Equations* (London: Forgotten Books)

Rosegrant M W, Ringler C, Msangi S, Sulser T B, Zhu T and Cline S A 2008 *International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description* (Washington, DC: International Food Policy Research Institute)

Rosenzweig C *et al* 2014 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison *Proc. Natl Acad. Sci.* **111** 3268–3273

Rounsevell M D A *et al* 2012 Challenges for land system science *Land Use Policy* **29** 899–910

Rutten M, van Dijk M, van Rooij W and Hilderink H 2014 Land use dynamics, climate change, and food security in Vietnam: a global-to-local modeling approach *World Dev.* **59** 29–46

Schmitz C *et al* 2014 Land-use change trajectories up to 2050: insights from a global agro-economic model comparison *Agric. Econ.* **45** 69–84

Schmitz C, Biewald A, Lotze-Campen H, Popp A, Dietrich J P, Bodirsky B, Krause M and Weindl I 2012 Trading more food: implications for land use, greenhouse gas emissions, and the food system *Glob. Environ. Change* **22** 189–209

Searchinger T, Heimlich R, Houghton R A, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D and Yu T-H 2008 Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change *Science* **319** 1238–1240

See L *et al* 2015 Building a hybrid land cover map with crowdsourcing and geographically weighted regression *ISPRS J. Photogramm. Remote Sens.* **103** 48–56

Siebert S, Burke J, Faures J M, Frenken K, Hoogeveen J, Döll P and Portmann F T 2010 Groundwater use for irrigation—a global inventory *Hydrol. Earth Syst. Sci.* **14** 1863–1880

Soares-Filho B S, Nepstad D C, Curran L M, Cerqueira G C, Garcia R A, Ramos C A, Voll E, McDonald A, Lefebvre P and Schlesinger P 2006 Modelling conservation in the Amazon basin *Nature* **440** 520–523

Sohngen B 2010 *An Analysis of Forestry Carbon Sequestration as a Response to Climate Change* (Copenhagen: Copenhagen Consensus Center)

Sohngen B and Brown S 2004 Measuring leakage from carbon projects in open economies: a stop timber harvesting

project in Bolivia as a case study *Can. J. Forest Res.* **34** 829–839
Sohngen B and Mendelsohn R 1998 Valuing the impact of large-scale ecological change in a market: the effect of climate change on US timber *Am. Econ. Rev.* **88** 686–710
Sohngen B and Mendelsohn R 2003 An optimal control model of forest carbon sequestration *Am. J. Agric. Econ.* **85** 448–457
Somé A, Dandres T, Gaudreault C, Majeau-Bettez G, Wood R and Samson R 2018 Coupling input-output tables with macro-life cycle assessment to assess worldwide impacts of biofuels transport policies *J. Ind. Ecol.* **22** 643–655
Song J, Delgado M, Preckel P V and Villoria N B 2018 Downscaling of national crop area statistics using drivers of cropland productivity measured at fine resolutions *PLoS One* **13** e0205152
Soterroni A C *et al* 2018 Future environmental and agricultural impacts of Brazil's forest code *Environ. Res. Lett.* **13** 74021
Stevanović M *et al* 2017 Mitigation strategies for greenhouse gas emissions from agriculture and land-use change: consequences for food prices *Environ. Sci. Technol.* **51** 365–374
Stevenson J R, Villoria N, Byerlee D, Kelley T and Maredia M 2013 Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production *Proc. Natl Acad. Sci.* **110** 8363–8368
Taheripour F and Tyner W 2013 Biofuels and land use change: applying recent evidence to model estimates *Appl. Sci.* **3** 14–38
Tilman D, Balzer C, Hill J and Befort B L 2011 Global food demand and the sustainable intensification of agriculture *Proc. Natl Acad. Sci.* **108** 20260–20264
Valbuena D, Verburg P H, Bregt A K and Ligtenberg A 2010 An agent-based approach to model land-use change at a regional scale *Landsc. Ecol.* **25** 185–199
van der Hilst F, Verstegen J A, Woltjer G, Smeets E M W and Faaij A P C 2018 Mapping land use changes resulting from biofuel production and the effect of mitigation measures *GCB Bioenergy* **10** 804–824
van der Mensbrugghe D 2013 Modeling the global economy—forward-looking scenarios for agriculture *Handbook of Computable General Equilibrium Modeling* vol 1 (Amsterdam: Elsevier) pp 933–994
Verburg P H, Ellis E C and Letourneau A 2011 A global assessment of market accessibility and market influence for global environmental change studies *Environ. Res. Lett.* **6** 34019
Verburg P H and Overmars K P 2009 Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model *Landsc. Ecol.* **24** 1167–1181
Verburg P H, Soepboer W, Veldkamp A, Limpiada R, Espaldon V and Mastura S S A 2002 Modeling the spatial dynamics of regional land use: the CLUE-S model *Environ. Manage.* **30** 391–405
Villoria N B 2019 Technology spillovers and land use change: empirical evidence from global agriculture *Am. J. Agric. Econ.* **101** 870–93
Villoria N B, Golub A, Byerlee D R and Stevenson J R 2013 Will yield improvements on the forest frontier reduce green house gas emissions? A global analysis of oil palm *Amer. J. Agri. Econom.* **95** 1301–08
Villoria N B and Hertel T W 2011 Geography matters: international trade patterns and the indirect land use effects of biofuels *Am. J. Agric. Econ.* **93** 919–935
Villoria N B and Liu J 2018 Using continental grids to improve understanding of global land supply responses: implications for policy-driven land use changes in the Americas *Land Use Policy* **75** 411–419
von Lampe M *et al* 2014 Why do global long-term scenarios for agriculture differ? An overview of the AgMIP global economic model intercomparison *Agric. Econ.* **45** 3–20
Wang M Q, Han J, Haq Z, Tyner W E, Wu M and Elgowainy A 2011 Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes *Biomass Bioenergy* **35** 1885–1896
West T A P, Grogan K A, Swisher M E, Caviglia-Harris J L, Sills E, Harris D, Roberts D and Putz F E 2018 A hybrid optimization-agent-based model of REDD+ payments to households on an old deforestation frontier in the Brazilian Amazon *Environ. Model. Softw.* **100** 159–174
Wiebe K *et al* 2015 Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios *Environ. Res. Lett.* **10** 85010
Wright C K, Larson B, Lark T J and Gibbs H K 2017 Recent grassland losses are concentrated around US ethanol refineries *Environ. Res. Lett.* **12** 44001
Yao G, Hertel T W and Taheripour F 2018 Economic drivers of telecoupling and terrestrial carbon fluxes in the global soybean complex *Glob. Environ. Change* **50** 190–200
Yu Y, Feng K and Hubacek K 2013 Tele-connecting local consumption to global land use *Glob. Environ. Change* **23** 1178–1186