Chapter 2
SIMPLE Economic Theory

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The SIMPLE modeling framework is firmly grounded in economic theory. As such, it is useful to review the foundational concepts before moving into the specification of the model itself, which is the subject of Part III of this book. This chapter introduces the theory of global land use change in the SIMPLE (global, non-gridded) framework, while Chap. 3 introduces the theory behind the gridded modeling. This economic theory part of the book is written for an interdisciplinary audience with an eye to making it broadly accessible. However, readers eager to get into the applications of SIMPLE-G are free to jump ahead, returning to this section as needed to understand the underlying theory, which will be referenced in many of the applications. Reading this chapter and Chap. 3 will enhance the readers' understanding of the economic mechanisms at work in SIMPLE-G.

1 One-Region Model: The Global Food System in a Nutshell

In the spirit of starting with the simplest possible economic model of global land use, we begin with a unified global agricultural economy (Fig. 2.1). We focus on cropland expansion in response to growth in demand for agricultural commodities (due to, e.g., growth in population, income, and biofuels). In this context, it seems intuitive that, if demand were to increase by 10% and farming techniques remained

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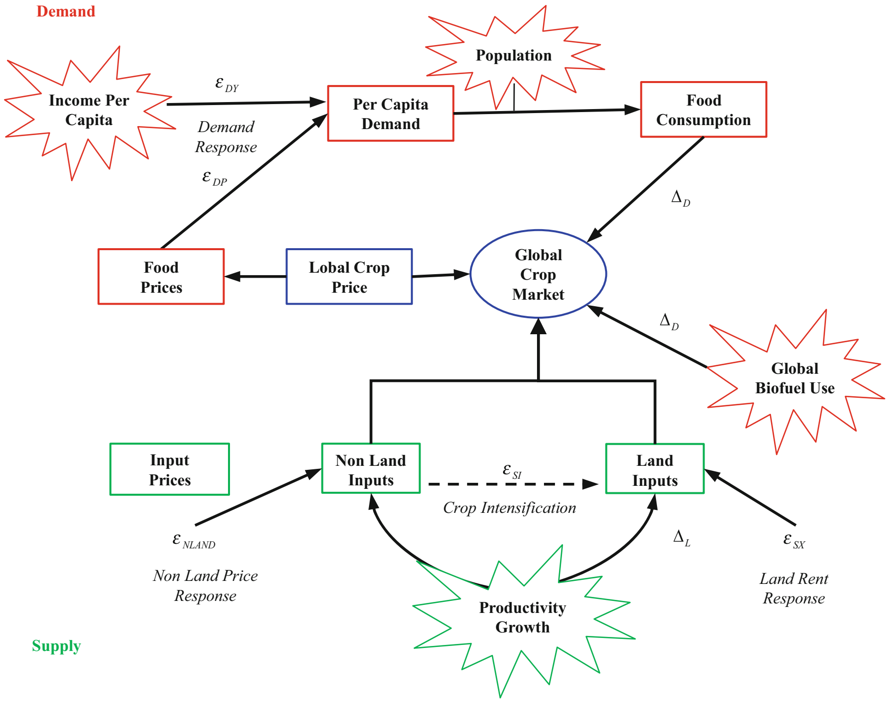

Fig. 2.1 The unified global economy. *Red outlines* denote demand factors while *green outlines* denote the supply side of the economy. Epsilon denotes elasticities while delta denotes shocks, or perturbations to the system

unaltered, the world would need 10% more land—of equivalent average quality—to meet the additional demand. However, historical data show that global production increased nearly fivefold over the five decades from 1961 to 2011, while the extent of global cropland increased only modestly (Fuglie et al. 2019). A large part of this difference can be explained by agricultural technologies, which experienced tremendous advancements over the same period. Among other things, many parts of the world have experienced the Green Revolution: Crop yields increased considerably through the introduction of new seed varieties and more intensive use of fertilizers and irrigation (Evenson and Gollin 2003). The intensity with which existing lands were cropped also increased significantly through double and even triple cropping (Bruinsma 2009). The modest net increase in cropland extent over this period is therefore an indication that, in the global footrace between growing demand and rising productivity, demand appears to have dominated. Although advances in technology have nearly kept pace with growing demand from an ever-richer global population.

The preceding narrative has abstracted from any economic factors. For example, we have not considered the response of consumers and producers to changes in the scarcity of cropland or food. As will be shown, these economic responses can be important in shaping the long-run evolution of land use. To see how these economic forces interact with biophysical factors (e.g., cropland extent, population growth, crop yield), consider Fig. 2.1, which introduces economic considerations (parameters shown in gray-shaded boxes and denoted with the epsilon symbol) into this discussion. On the demand side, it has been well documented that people tend to initially consume more food as their incomes rise from low levels. The parameter $\varepsilon_{\mathrm{DY}}(y)$ captures this effect and is known to economists as the income elasticity of demand for food. In addition, as incomes rise, consumers also tend to shift their consumption patterns toward more livestock-based products (Pingali 2007), with important consequences for land use. Livestock—particularly cattle—are relatively poor converters of land into food (Eshel et al. 2014). In addition to responding to changing incomes, consumer demand is also price responsive. The absolute value of price responsiveness—also called the price elasticity of food demand, $\varepsilon_{\mathrm{DP}}(y)$—tends to diminish as consumers become wealthier (Muhammad et al. 2011). This is reflected in the fact that the price elasticity is itself a function of per capita income. High-income consumers can largely ignore rising prices of a commodity (e.g., rice), which accounts for just a small share of their total budget, whereas low-income consumers must adjust by either consuming less food or switching to food sources that are cheaper per calorie provided.

Economic factors also play a role in the supply side of the global food economy, as illustrated in the lower half of Fig. 2.1. As land becomes increasingly scarce in the face of growing demand, land prices (and farmland rental prices) rise. During boom periods, these land rental responses can be very large (Henderson et al. 2011), and they send signals to farmers to conserve land by intensifying production. This response is captured by $\varepsilon_{\mathrm{SI}}$, referred to as the price elasticity of supply at the intensive margin (i.e., the price responsiveness of crop yields). In the long run, research and development and the adoption of agricultural technologies have also been shown to respond to relative prices (Ruttan 1977), with the effect of further increasing the value of $\varepsilon_{\mathrm{SI}}$.

The potential for intensification of crop production depends on a variety of agronomic and economic factors and on the current level of intensification. It is expected that a favorable development in prices (e.g., higher output prices or lower input prices) could induce a significant supply response at this intensive margin in parts of the world with very low levels of commercial inputs. This has been found to be the case in Malawi, where significant fertilizer subsidies were introduced to increase maize production (Ricker-Gilbert et al. 2011). However, the magnitude of this response has been vigorously debated and clearly depends on a variety of other local factors, including the extent of soil degradation (Messina et al. 2017). This raises broader questions about the extent to which biophysical and socioeconomic constraints might alter producers' ability to respond to higher prices at the intensive margin.

Location is clearly a critical factor in environmental policy analysis, but many global economic models of land use change do not differentiate yield response by location. The greater the yield response to scarcity, the less the need to convert natural lands to cropland in the face of shocks (e.g., the US biofuels boom). Golub and Hertel (2012) show that when yield responses in non-US regions are allowed to depart from US-based estimates in the widely used GTAP-BIO model, dramatically different estimates of global land use and terrestrial carbon emissions as a result of the US biofuels mandates are obtained. They conclude that more geographically specific estimates of the endogenous intensification parameter, $\varepsilon_{\mathrm{SI}}$, are required to accurately estimate cropland expansion. Havlik et al. (2013) have sought to introduce regional heterogeneity into their global model (GLOBIOM) by explicitly modeling the biophysical and economic systems at the grid cell level and then aggregating these systems at the national and global levels. Their linear programming approach is an important starting point; however, there is little doubt that much more research is required to accurately estimate location-specific intensive margins of supply response across the globe.

The final piece of this economic puzzle is the responsiveness of cropland supply to increased returns in farming. This parameter, $\varepsilon_{\mathrm{SX}}$, called the price elasticity of supply at the extensive margin, is shown at the bottom of Fig. 2.1. In this simplified, long-run, partial equilibrium framework, we assume that nonland inputs are in "perfectly elastic" supply. This means that the nonland input prices are unaffected by developments in the farm sector and are instead determined by developments in the rest of the economy. We will relax this assumption in Chap. 3, showing that the responsiveness of the price of other inputs, such as labor, to developments in the farm sector can be very important for sustainability and equity outcomes.

The economic elements introduced above can be combined to allow for an analytical, partial equilibrium solution to this unified agricultural model. The resulting analytical solution (Eq. 2.1) expresses the long-run change in cropland, q_L^*, as being dependent on the exogenous shocks to demand, Δ_D; exogenous trends in yields due to improvements in agricultural technology, Δ_L, and the three economic margins (elasticities) of response to price:

$$q_L^* = (\Delta_D - \Delta_L)/(1 + \varepsilon_{\mathrm{SI}}/\varepsilon_{\mathrm{SX}} + \varepsilon_{\mathrm{DP}}/\varepsilon_{\mathrm{SX}}) \tag{2.1}$$

Equation (2.1) reveals several important points about long-run global cropland change. First, since all price elasticities are defined as positive, their presence in the denominator of Eq. (2.1) serves as a shock absorber to global land use changes in response to changes in net demand for cropland ($\Delta_D - \Delta_L$). If the world finds itself in a period in which demand for cropland is outstripping yield-improving innovations, then prices will rise, households will curb consumption or shift to less land-intensive diets (e.g., less beef), and farmers will intensify production. All these responses will lead to a moderation in the amount of additional land actually brought under cultivation.

A second point to note from Eq. (2.1) is that what matters for land conversion is not the absolute size of the price elasticities of demand and supply but rather the relative size of the demand and intensive (yield response) supply elasticities compared to the extensive (area response) supply response. There are many examples of biophysical models of global cropland change that do not incorporate the demand

and intensive supply margins into their long-run projections. Historically, the GCAM (Wise and Calvin 2011), IMAGE (PBL Netherlands Environmental Assessment Agency 2015), and PIK models (Lotze-Campen et al. 2008) all fell into this category, although more recent versions have sought to remedy this limitation in various ways. In Eq. (2.1), ignoring these demand and supply intensive margins is equivalent to assuming that $\varepsilon_{\mathrm{SI}} = \varepsilon_{\mathrm{DP}} = 0$. In this case, when net demand rises by 10%, (productivity-adjusted) global cropland must also rise by 10%.

Baldos and Hertel (2013) explore the implications of ignoring these economic margins of response in the context of the 1961–2006 period for the global food economy (1961 is when the FAO data series begins, and 2006 is the year before a major global food price crisis). They first introduce the SIMPLE model (a Simplified International Model of Prices, Land use, and the Environment) and validate it against global data over this period. SIMPLE is a numerical implementation of the framework shown in Fig. 2.1 (see Part III for more details). Supply and demand in SIMPLE are developed at the level of geographic regions, and growth in population, income, and productivity are specified exogenously. The authors find that, when they run the model over this historical period with the demand and intensive supply margins eliminated (i.e., $\varepsilon_{\mathrm{SI}} = \varepsilon_{\mathrm{DP}} = 0$), the model overpredicts historical land use change nearly threefold. This illustrates the point, already evident from Eq. (2.1), that purely biophysical models will overstate cropland changes in response to exogenous shocks. This follows directly from the missing adjustments in consumer demand and producer yields in response to higher prices. It also helps to explain why some of the most prominent Integrated Assessment Models predict considerable expansion in cropland over the twenty-first century (Schmitz et al. 2014) despite slowing population growth (UN) and robust growth in agricultural productivity (Fuglie 2010). In short, land use change scientists ignore economic responses to scarcity at their peril when undertaking long-run projections of land use change.

One of the important conservation policies that we will consider in this book involves the withdrawal of land and/or water from agriculture, in favor of environmental uses. In our stylized framework, this introduces a backward shift in cropland supply, represented by Δ_S. This results in a modified version of Eq. (2.1):

$$q_L^* = \{(\Delta_D + \Delta_S - \Delta_L)/(1 + \varepsilon_{\mathrm{SI}}/\varepsilon_{\mathrm{SX}} + \varepsilon_{\mathrm{DP}}/\varepsilon_{\mathrm{SX}})\} - \Delta_S \tag{2.2}$$

In the absence of any demand or intensive margin response (i.e., $\varepsilon_{\mathrm{SI}} = \varepsilon_{\mathrm{DP}} = 0$), this new term cancels out and does not influence the total land use outcome. In other words, if land is withdrawn in one location, it must expand somewhere else in order to satisfy a fixed level of global food demand. However, if the economic margins of demand and supply are price responsive, then this conservation policy will have a more nuanced impact, making land scarcer and raising prices. For example, if all three price elasticities were equal in absolute magnitude, then only one-third of the land set-aside would be replaced by expansion elsewhere. In this context, the conservation policy is more effective, as it now has a chance to operate on the intensive margin of supply as well as on the demand margin. In the—admittedly naïve—case of equal elasticities, two-thirds of the land conservation target would be effectively achieved—in equal parts—by reductions in demand and expansion in yields. Clearly, the success of environmental policies aiming to remove sensitive natural resources from agricultural production depends on economic responses to the conservation measures.

2 Two-Region Model: International Trade Creates Opportunities for Land Use Spillovers to Other Regions

Thus far in our model of global land use change, we have abstracted from international trade by assuming a unified global economy in which any shock (e.g., an improvement in technology or a conservation policy) applies worldwide. However, most of the empirical literature on land use spillovers and leakage focuses on cases in which producers in one region are "treated" with technological change or conservation set-asides and the remainder of the global economy is "untreated" (Angelsen and Kaimowitz 2001; Gasparri et al. 2016; le Polain de Waroux et al. 2019). Here, economic theory can again provide useful insights by shedding light on the conditions under which improvements in agricultural technology will lead to land expansion in the treated region.

In this analysis, we start with the simplest case—again, admittedly naïve—in which world markets for agricultural products are fully integrated. This specification—which might be termed trade economist nirvana—reflects a global economy in which the farm commodity can be purchased for the same price regardless of country or region. Therefore, we are abstracting from all trade frictions, such as transport costs, tariffs, and other government policies aimed at insulating domestic producers and/or consumers from developments in world markets. The three-panel diagram in Fig. 2.2 depicts this situation. The left-hand panel portrays an increase in agricultural commodity supply, for any given price, in innovating Region A, via an outward shift in the supply curve. The supply curve in the

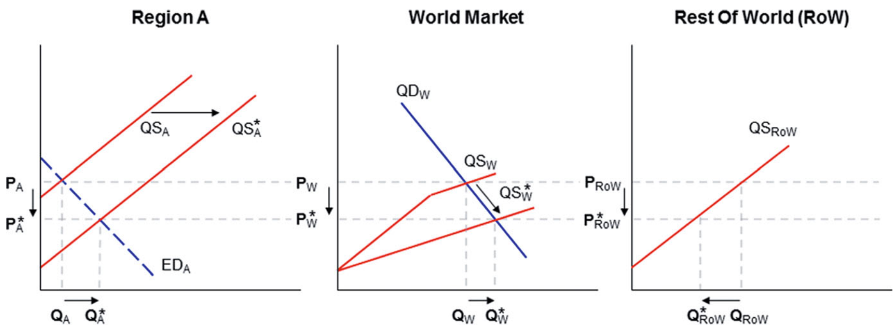

Fig. 2.2 Impact of a technological improvement in Region A on the world market and on the rest of the world

non-innovating rest of the world (RoW) remains unchanged, as shown in the righthand panel. The middle panel portrays global market equilibrium under integrated markets, where Region A's supply is added to that from the RoW to obtain a global supply curve. The intersection of global supply and demand determines world price, which naturally falls in response to the increased product supply coming from Region A.

The productivity gain shifts the supply curve in Region A—and hence the world—to the right, thereby depressing the world price and, as a consequence, production in other regions.

In this framework, the sufficient statistic for determining the direction of land use change in a region in response to an improvement in agricultural technology is the absolute value of the price elasticity of excess demand facing producers in the technology-advancing region (Hertel et al. 2014). This elasticity is denoted $\varepsilon_{\mathrm{DP}}^{T}$, where superscript T denotes its association with the technically innovating region. It is governed by the slope of the demand curve facing producers in the innovating region (dashed line, labeled EDA in Fig. 2.2). The expression for $\varepsilon_{\mathrm{DP}}^{T}$ is given by Eq. (2.3), which shows that the excess demand elasticity depends not only on global demand conditions ($\varepsilon_{\mathrm{DP}}^{W}$) but also on the responsiveness of RoW producers $\left(\varepsilon_{\mathrm{SI}}^{\mathrm{RoW}} + \varepsilon_{\mathrm{SX}}^{\mathrm{RoW}}\right)$ to price changes emanating from the innovating region.

$$\varepsilon_{\mathrm{DP}}^{T} = \left[\varepsilon_{\mathrm{DP}}^{W} + (1-\alpha)\left(\varepsilon_{\mathrm{SI}}^{\mathrm{RoW}} + \varepsilon_{\mathrm{SX}}^{\mathrm{RoW}}\right)\right]/\alpha \tag{2.3}$$

When $\varepsilon_{\mathrm{DP}}^{T}$ is large, producers in Region A can expand production without significantly affecting the world price for the crop in question. When $\varepsilon_{\mathrm{DP}}^{T}$ is small, the expansion drives prices down and limits the incentive for further expansion.

The share of global supply provided by the innovating region, denoted α, also plays a critical role. The smaller this share is, the larger the excess demand elasticity will be. As shown in Hertel et al. (2014), the critical value for determining the direction of land use change in the innovating region is $\varepsilon_{\mathrm{DP}}^{T} = 1$. When $\varepsilon_{\mathrm{DP}}^{T} > 1$, improvements in productivity will lead to cropland expansion in the innovating region. When $\varepsilon_{\mathrm{DP}}^{T} < 1$, the price-depressing effect of output expansion will curb production (i.e., the efficiency gains of the new technology will outweigh the effect of increased output) and land use in the innovating region will contract.

This analytical framework is extremely useful for sorting out the literature that has emerged from the Borlaug–Jevons debate on the land use impacts of agricultural technology change (Hertel et al. 2014). First, it is clear from Eq. (2.3) that, contrary to assertions in much of the early literature on this topic (Angelsen and Kaimowitz 2001), the question cannot be answered simply by observing global demand conditions for the innovated product; the supply response in the rest of the world is also critically important. Second, given the important role of α in Eq. (2.3), if an innovating region has only a small share of the global market, it is more likely that $\varepsilon_{\mathrm{DP}}^{T} > 1$ and land expansion will occur in the innovating region. This highlights the importance of being a small producer in the world market. Under these conditions, land use expansion in the innovating region becomes more likely. Villoria (2019) provides an empirical analysis, of the impact of national productivity improvements on domestic farmland expansion. He finds that technological improvements in most countries in the world lead to national land use expansion in the innovating region. However, in a few large and/or relatively closed economies (e.g., China and India), he finds that domestic productivity improvements have led to land conservation in that country.

To this point, we have not yet addressed the fundamental question of global land use, which was at the heart of Borlaug's (2007) assertion that the Green Revolution had spared land worldwide. Determining the conditions under which improved technology in one region will spare land globally is more complex than determining land use change in the innovating region alone. Economic theory dictates that with a lower world price, output and land use will fall in the non-innovating regions in the wake of the new technology, assuming that this is the only change occurring in the global economy. However, the decline in land use overseas could be offset by a rise in land use in the innovating region. Ultimately, Borlaug's hypothesis requires testing in an empirical context. However, if we assume that the supply elasticities are equal in both regions, we can derive Eq. (2.4) to highlight the critical role of relative yields in this debate. This equation states that Borlaug's hypothesis will be overturned when the price elasticity of world demand for the crop in question exceeds a weighted combination of relative yields in the innovating region versus globally (Y^A/Y^W) and the globally uniform total supply response to price (ε_S^W) under the condition of equal supply elasticities:

$$\varepsilon_{\mathrm{DP}}^W > \left(Y^A/Y^W\right)\left(\varepsilon_S^W + 1\right) - \varepsilon_S^W \Rightarrow \text{rejectBorlaug} \tag{2.4}$$

It is easy to see from Eq. (2.4) that the terms involving the supply elasticity would cancel if yields were the same between the treated and untreated regions. In this case, the critical value required for Borlaug's assertion to hold is that the global price elasticity of demand for the crop in question be less than 1. Since this is true for most staple foods in most regions (Muhammad et al. 2011), given the Green Revolution's emphasis on staple grains, Borlaug would seem to be strongly supported by the condition in Eq. (2.4).

However, what if yields in the two regions were unequal? In particular, what if yields in the innovating region are far lower than the world average (i.e., $Y^A/Y^W \ll 1$)? This opens the possibility of Jevons' paradox applying at global scale. Hertel et al. (2014) explore this possibility in greater detail using the SIMPLE model developed in Chap. 4 of this book and relax the restrictive assumptions about equal supply responses in the two regions. They find that, while the historical Green Revolution did indeed spare land globally, a prospective African Green Revolution might not have the same benefit due to very low relative crop yields in in sub-Saharan Africa. This is particularly likely if global markets were fully integrated, such that each commodity had a uniform price worldwide.

3 Segmented Markets: Product Differentiation Blunts the Cross-Border Transmission of Price Signals

The (increasingly challenged) efforts of the World Trade Organization (WTO) notwithstanding, the world is a long way from the stylized model of perfectly integrated global markets postulated in the foregoing analysis. This is particularly true for agricultural products for which government interventions remain pervasive. Indeed, agriculture is one of the primary reasons why the Doha Round of WTO trade negotiations was inconclusive (WTO 2018). In some regions—most notably parts of sub-Saharan Africa (SSA)—there is the added challenge of physical access to markets. Producers and consumers are isolated, not only from international markets but also from their own national markets (Porteous 2015). We adopt the term *market segmentation* to refer to a situation in which markets are not fully connected and international prices are imperfectly transmitted into national and local markets, due either to government policies or to poor infrastructure and weak logistics. This has the effect of reducing the excess demand elasticity in Eq. (2.3), thereby increasing the likelihood that an improvement in locally employed agricultural technology will reduce the extent of local cropland.

Regardless of the extent of market integration, we already know that if the technological innovation in the innovating region is the only perturbation to the system, then cropland in the rest of the world must fall (or at least not rise, relative to baseline) due to the expected decline in world prices. Therefore, a simultaneous decline in land use in the innovating region is a sufficient condition to satisfy the Borlaug hypothesis. By reducing the excess demand elasticity facing producers in the innovating region, market segmentation reinforces the Borlaug intuition. Hertel et al. (2014) confirm this point empirically by examining the impact of a prospective African Green Revolution in the presence of historically segmented agricultural markets. They conclude that, under this historical trade regime, such a future Green Revolution would indeed be land sparing, in contrast to the ambiguous outcome when markets are perfectly integrated. In summary, the extent of market integration is a key determinant of the sustainability of agricultural innovations as well as many other interventions in the global food system.

4 Summary

The one-region model of the global food system provides a simplified framework to understand the economic relationship between demand and supply factors and their impacts on land use. While the model abstracts from the complexities of the real world, it highlights the importance of technological change in increasing agricultural productivity and the role of economic responses to scarcity in shaping land use patterns. The model also suggests that intensification of crop production can be a viable strategy to meet growing demand, but its potential is constrained by a range of agronomic, environmental, and economic considerations. Understanding these factors is crucial for designing effective policies that promote sustainable land use and food security in the face of global challenges such as population growth, climate change, and resource scarcity. The two-region conceptual framework highlights the interplay between market developments in one part of the world and the consequences for outcomes elsewhere, as well as global environmental impacts. This framework highlights the role of market integration in determining the sustainability of agricultural innovations in the global food system.

References

Angelsen, A., and D. Kaimowitz, eds. 2001. *Agricultural technologies and tropical deforestation*. Wallingford: CAB International. https://doi.org/10.1079/9780851994512.0000.

Baldos, Uris Lantz C., and Thomas W. Hertel. 2013. Looking back to move forward on model validation: Insights from a global model of agricultural land use. *Environmental Research Letters* 8: 034024. https://doi.org/10.1088/1748-9326/8/3/034024.

Borlaug, Norman. 2007. Feeding a hungry world. *Science* 318: 359–359. https://doi.org/10.1126/science.1151062.

Bruinsma, Jelle. 2009. The Resource Outlook to 2050: By how much do land, water and crop yields need to increase by 2050? In *FAO Expert Meeting on How to Feed the World in 2050*. Rome: Food and Agriculture Organization of the United Nations Economic and Social Development Department.

Dietrich, Jan Philipp, Christoph Schmitz, Hermann Lotze-Campen, Alexander Popp, and Christoph Müller. 2014. Forecasting technological change in agriculture—An endogenous implementation in a global land use model. *Technological Forecasting and Social Change* 81: 236–249. https://doi.org/10.1016/j.techfore.2013.02.003.

Eshel, Gidon, Alon Shepon, Tamar Makov, and Ron Milo. 2014. Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. *Proceedings of the National Academy of Sciences* 111: 11996–12001. https://doi.org/10.1073/pnas.1402183111.

Evenson, R.E., and D. Gollin. 2003. Assessing the impact of the green revolution, 1960 to 2000. *Science* 300: 758–762. https://doi.org/10.1126/science.1078710.

Fuglie, Keith. 2010. Total factor productivity in the global agricultural economy: Evidence from FAO data. In *The shifting patterns of agricultural production and productivity worldwide*, 63–95. Ames: The Midwest Agribusiness Trade Research and Information Center, Iowa State University.

Fuglie, Keith, Madhur Gautam, Aparajita Goyal, and William F. Maloney. 2019. *Harvesting prosperity: Technology and productivity growth in agriculture*. Washington, DC: World Bank. https://doi.org/10.1596/978-1-4648-1393-1.

Gasparri, Nestor Ignacio, Tobias Kuemmerle, Patrick Meyfroidt, Yann le Polain, and de Waroux, and Holger Kreft. 2016. The emerging soybean production frontier in southern Africa: Conservation challenges and the role of south-south telecouplings. *Conservation Letters* 9: 21–31. https://doi.org/10.1111/conl.12173.

Golub, Alla A., and Thomas W. Hertel. 2012. Modeling land-use change impacts of biofuels in the GTAP-BIO framework. *Climate Change Economics* 3: 1250015. https://doi.org/10.1142/S2010007812500157.

Havlík, Petr, Hugo Valin, Aline Mosnier, Michael Obersteiner, Justin S. Baker, Mario Herrero, Mariana C. Rufino, and Erwin Schmid. 2013. Crop productivity and the global livestock sector:

Implications for land use change and greenhouse gas emissions. *American Journal of Agricultural Economics* 95: 442–448. https://doi.org/10.1093/ajae/aas085.

Henderson, Jason, Brent A. Gloy, and Michael D. Boehlje. 2011. Agriculture's boom-bust cycles: Is this time different? *Economic Review* 96: 81–103.

Hertel, Thomas W. 2018. Economic perspectives on land use change and leakage. *Environmental Research Letters* 13: 075012. https://doi.org/10.1088/1748-9326/aad2a4.

Hertel, Thomas W., Navin Ramankutty, Lantz C. Uris, and Baldos. 2014. Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO2 emissions. *Proceedings of the National Academy of Sciences* 111: 13799–13804. https://doi.org/10.1073/pnas.1403543111.

le Polain de Waroux, Yann, Rachael D. Garrett, Jordan Graesser, Christoph Nolte, Christopher White, and Eric F. Lambi. 2019. The restructuring of South American soy and beef production and trade under changing environmental regulations. *World Development* 121: 188–202. https://doi.org/10.1016/j.worlddev.2017.05.034.

Lotze-Campen, Hermann, Christoph Müller, Alberte Bondeau, Stefanie Rost, Alexander Popp, and Wolfgang Lucht. 2008. Global food demand, productivity growth, and the scarcity of land and water resources: A spatially explicit mathematical programming approach. *Agricultural Economics* 39: 325–338. https://doi.org/10.1111/j.1574-0862.2008.00336.x.

Messina, Joseph P., Brad G. Peter, and Sieglinde S. Snapp. 2017. Re-evaluating the Malawian Farm Input Subsidy Programme. *Nature Plants* 3: 17013. https://doi.org/10.1038/nplants.2017.13.

Muhammad, Andrew, James L. Seale Jr., Birgit Meade, and Anita Regmi. 2011. *International evidence on food consumption patterns: An update using 2005 international comparison program data*, Technical Bulletin 1929. Washington, DC: US Department of Agriculture, Economic Research Service.

PBL Netherlands Environmental Assessment Agency. 2015. Welcome to IMAGE 3.0 Documentation. https://web.archive.org/web/20151108083904/http://themasites.pbl.nl/models/image/index.php/Welcome_to_IMAGE_3.0_Documentation.

Pingali, Prabhu. 2007. Westernization of Asian diets and the transformation of food systems: Implications for research and policy. *Food Policy* 32: 281–298. https://doi.org/10.1016/j.foodpol.2006.08.001.

Porteous, Obie C. 2015. High trade costs and their consequences: An estimated model of African agricultural storage and trade. In *Joint Annual Meeting*. San Francisco: Agricultural and Applied Economics Association & Western Agricultural Economics Association. https://doi.org/10.22004/ag.econ.205776.

Ricker-Gilbert, Jacob, Thomas S. Jayne, and Ephraim Chirwa. 2011. Subsidies and crowding out: A double-hurdle model of fertilizer demand in Malawi. *American Journal of Agricultural Economics* 93: 26–42. https://doi.org/10.1093/ajae/aaq122.

Ruttan, Vernon W. 1977. Induced innovation and agricultural development. *Food Policy* 2: 196–216. https://doi.org/10.1016/0306-9192(77)90080-X.

Schmitz, Christoph, Hans Van Meijl, Page Kyle, Gerald C. Nelson, Shinichiro Fujimori, Angelo Gurgel, Petr Havlik, et al. 2014. Land-use change trajectories up to 2050: Insights from a global agro-economic model comparison. *Agricultural Economics* 45: 69–84. https://doi.org/10.1111/agec.12090.

Villoria, Nelson. 2019. Consequences of agricultural total factor productivity growth for the sustainability of global farming: Accounting for direct and indirect land use effects. *Environmental Research Letters* 14: 125002. https://doi.org/10.1088/1748-9326/ab4f57.

Wise, M., and K. Calvin. 2011. *GCAM 3.0 agriculture and land use: Technical description of modeling approach*, PNNL-20971. Richland: Pacific Northwest National Laboratory.

World Trade Organization. 2018. The Doha Round. https://www.wto.org/english/tratop_e/dda_e/dda_e.htm. Accessed 1 Feb 2024.