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Bridging the Divide Between Agricultural Economics and the Sustainability Sciences[1]

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Bridging the Divide Between Agricultural Economics and the Sustainability Sciences[1]

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Abstract: This lecture is based on several decades of experience engaging in interdisciplinary research and teaching involving agronomists, climate scientists, ecologists, hydrologists and geographers, focused on ensuring the long run sustainability of local and global food systems. Through a series of examples of this research, the paper will underscore several key points. The first is that keeping the economics as simple as possible leaves greater room for interdisciplinary collaboration. The more complex the economic models, the higher the barrier to effective collaboration. Basic economic messages on the role of markets in mediating the impacts of policies, along with producer and consumer responses to changing incentives are invaluable to sustainability analyses and can lend important new insights. This doesn't mean that the ensuing economic analysis is not sophisticated. Indeed, as will be demonstrated, sophisticated analysis is critically important. But this analysis is at the 'extensive margin' of economic science – applying established methods to new application domains.

A second point is that economists must work at the same spatial resolution as our science collaborators. For food, land and water sustainability challenges, this is typically the grid cell. Economists have been slow on the uptake of the geospatial data revolution. For me personally, this has meant moving, over the last two decades, from national scale general equilibrium modeling to gridded partial equilibrium modeling. Ultimately, these two frameworks can be combined, as I will demonstrate in this talk. However, many sustainability analyses must start at the granular level where one can leverage the full expertise of the biophysical scientists. This may take many economists out of their comfort zone. However, as I will demonstrate in this talk, our tools can be adapted and brought to bear at fine scale. In this context, I will also highlight the value of the Global-to-Local-to-Global approach to sustainability analysis.

The third key point made in this talk is that economics offers a great organizing framework for interdisciplinary projects. Too often we let the biophysical scientists frame the discussion prior to our involvement. This leads to frustration on the part of economists who are relegated to a secondary role in the project. However, if we lead the writing of the proposal and frame the overall discussion in economic terms, this gives rise to a very different dynamic which can facilitate coherent and meaningful economic analyses. Further, when economics is NOT used in the sustainability sciences, policy prescriptions are often limited at best, and misleading at worst.

Finally, I have some suggestions for the teaching of interdisciplinary skills at the graduate level. Here, a well-constructed course can benefit both the students, as well as the professor, fostering fruitful collaborations on grant applications, as well as generating new ideas for research in the sustainability sciences.

I. A Century of Agricultural Economics—and a New Century of Challenges

It is an honor to be invited to give this address on the occasion of the 100th Anniversary of the UK Agricultural Economics Society. The Society has made many contributions to the Agricultural Economics Profession and it has often been at the forefront of efforts to bridge between agricultural economics and other disciplines to address a wide range of policy challenges (Blandford, 2026). It is in the spirit of such bridging that my talk today will discuss the importance of agricultural economics within the broader context of sustainability sciences.

I will make the case that our profession has a great deal to contribute – indeed absent our contributions, many of the sustainability policy prescriptions are likely to be ineffective at best and potentially seriously misleading. However, in order to have an impact, we need to rethink the way we collaborate with the biophysical sciences. Indeed, we are often marginalized when it comes to the broader public debate, with the headlines being dominated by doomsday predictions with little policy relevance.

I will present three core arguments in this talk. First, I will argue that we need to keep our economic models as simple as possible to allow for deep integration with the other disciplines. Here, I will echo some of the arguments made in Brendan Bayley's 2023 AES Presidential Address where he argues that "Basic economic concepts, and paying attention to how things work, and why, in agricultural markets, can generate important insights; they should be the starting point for any modeling work." (Bayley 2024). The sophistication in successful interdisciplinary collaborations comes at the 'extensive margin' in the form of novel approaches for imbedding the biophysical insights into the economic framework.

The second point I will make in this paper is that we, as economists, need to meet our science collaborators at the spatial scale which is most appropriate for the sustainability analysis. This typically involves employing a gridded economic approach, although, as I will show, this does not preclude embedding the analysis within a global economic model. Finally, I will discuss approaches to developing the next generation of agricultural and applied economists who can readily bridge our discipline with others working in the sustainability sciences.

II. The Case for Simplicity

A. The Collaboration Paradox: Less Can Be More

I must confess that there was a time in my career when my work focused on taking a simple problem and making it more complex. One of the easiest ways to do so is to introduce more flexible mathematical functions to represent producer and consumer behavior. This opens the possibility for many interesting, and sometimes counterintuitive, policy impacts (Hertel 1988). However, it quickly renders the modeling and policy analysis impenetrable to all but the most determined economists. Similarly, I have devoted a good part of my career to general equilibrium analysis (Hertel, 2012). As we will see in this talk, that has its place in the sustainability science toolkit. However, as with the flexible functional forms, at times it can also make things unnecessarily complex. A third area where I have worked, building on my early days as a resource economist, is in intertemporal dynamics. Introducing forward-looking behavior can be essential for some sustainability problems (Steinbuks and Hertel 2014), but, in my experience, this can also render the model inaccessible to many collaborators. And if you really want to have a mess – try integrating all three of these features of into a single economic model! In this paper I will make the case that *less is more* when it comes to transdisciplinary collaboration. Simple economic frameworks can be of great value in such contexts.

By way of illustration, let me draw on two attempts at interdisciplinary collaboration – one successful and one not. Let's start with the latter case. I was part of a large-scale, long run collaboration between climate scientists, economists and statisticians aimed at shedding light on climate mitigation and adaptation. At our kick-off meeting, lead scientists from each field were asked to give a short talk on key insights from their field that might bear on the collaboration envisioned. Most of the scientists spoke for 10-15 minutes accompanied by visual aids, allowing time for interaction and discussion of implications for the collaborative project. However, the Nobel Laureate Economist on this project proceeded to fill the white board with equations, which most of the scientists in the room had trouble following. This presentation went on for more than half an hour, leaving no time for discussion. These remarks, however brilliant, had virtually no impact on the trajectory of this project. As economists we must recognize where our most impactful contributions to such interdisciplinary projects may lie. This is usually in the domain of simplified economic models.

In sharp contrast to the preceding experience, I was pleasantly surprised in the context of an interdisciplinary collaboration with hydrologists for which we were focusing on groundwater sustainability. We had developed a simple economic model (more on this below) which allowed for both increased intensity of irrigation, as well as expansion in irrigated area. As we were interpreting some of the early model simulations, the hydrologist collaborator made the observation: "Yes, but isn't your explanation ignoring the intensive margin?" She was right! Not only had she internalized the essence of our economic model, but she reminded us that we were ignoring a key economic response to water scarcity! I view this collaboration as a great success!

In general, a good starting point in interdisciplinary collaborations is to emphasize the key role for markets and prices, and the ensuing producer and consumer responses. Many sustainability scientists operate under the implicit assumption that they can directly control the actions of farmers, agribusinesses and consumers. This leads to policy pronouncements such as: ‘don’t worry about the induced land use impacts of second-generation biofuels – we will grow the feedstocks on marginal lands’ (e.g., Russo et al. 2025). This carries the implicit assumption that the scientist gets to direct the pattern of crop cultivation – leaving no role for markets and prices. Absent meaningful policy recommendations for a decentralized market economy, such analyses, while potentially publishable in top scientific journals, are destined to have little impact on policy.

I first came to realize the power of simplicity in interdisciplinary analysis in the wake of my 2010 AAEA Presidential Address which focused on the determinants of the global supply and demand for land in the 21st century. Written at the time of the biofuels boom and the accompanying food price crisis, I developed a simple analytical framework designed to capture the many competing forces at work, including demographic change, income growth, biofuel mandates, growing demands for land-based ecosystem services, climate change and technological innovation. The solution to this model -- a single equation describing the evolution of future land use – highlighted the role of economic responses to scarcity (both demand and supply-side) as ‘shock absorbers’, lessening the impact of demand growth on farmland expansion. If they were ignored, scientists would over-estimate future land use change. This was a novel insight at the time and it is was further underscored by several interdisciplinary efforts to project farm land use in the 21st century which resulted a dramatic over-estimates of cropland expansion (Hertel et al. 2016).

By way of illustration, over the period: 1961-2011, global crop production tripled, yet the rate of global cropland expansion amounted to just 14% (Bruinsma 2009). Yet, with population growth slowing – and indeed total population declining in many countries, projections to mid-century (2006-2050) by a number of the AgMIP global economic models showed higher rates of cropland growth than for a comparable historical period (Hertel et al. 2016), with models projecting as much as twice the earlier rate of cropland growth. In undertaking a deeper dive into model parameterization, Hertel et al. (2016) (Table 3) discovered that many of these models largely ignored the intensive margin of supply response. In addition, some models also ignored the price responsive nature of consumer demand for food. It is no wonder that such models would be overpredicting expansion at the extensive margin (more cropland) as the single equation model solution referenced above had demonstrated.

Based on the favorable response to this simple analytical model employed in the AAEA Presidential Address, I ventured to develop, in collaboration with my colleague Uris Baldos, a quantitative version of this model for use in an interdisciplinary graduate course on the global food system and environmental sustainability (Hertel and Baldos 2016). We named the model SIMPLE (a Simplified International Model of Prices Land use and the Environment -- see also Figure 1). This model strives to incorporate, for each world region, key economic drivers of, and responses to, sustainability stresses. Food demands are driven by crop, livestock, processed food and biofuel consumption, which, in turn are driven by population, income, prices, and government mandates. Price and income elasticities of demand evolve with income, following the empirical literature (Hertel and Baldos, 2016). On the supply side, land and nonland inputs are distinguished, each with their own factor supply elasticities and together determine the extensive margin of supply response. Substitution of nonland for land inputs is governed by an elasticity which determines the intensive margin of supply response. Productivity growth is the key driver of long-run agricultural supply and it is a function of R&D stocks as well as climate. Equilibrium is attained when local supplies equal local demands and global markets clear. Domestic and global markets are linked via Armington elasticities of demand for imports as well as export supplies.

The SIMPLE model was designed for teaching purposes (more on the teaching side of this story below). However, we quickly found that it was also useful for answering research questions which arose in the classroom. One of the first publications (Baldos and Hertel 2013) sought to delve more deeply into the question of global cropland projections. Heavily influenced by my collaborations with climate scientists, we began by looking backward in time, from 2006 to 1961 (the year current FAO time series national statistics begin). This provided a natural precursor for forward projections, over a comparable timespan, from 2006-2050. Happily, we found that the SIMPLE model did a pretty good job projecting global crop production, prices and land use over the historical period. (We also learned that it is much easier to project global outcomes than those at the regional level!) We then used this historical 'laboratory' to explore the implications of omitting key economic mechanisms in the global food system.

In the 2013 paper, we considered a variety of economic misspecifications/omissions and their implications for historical land use predictions. Most striking was the impact of omitting the intensive margin of supply (i.e., rendering long run crop yield growth rates unresponsive to prices). This resulted in massive over-predictions of the global cropland conversion, for the historical period: 1961-2006. Failing to allow income elasticities of demand to evolve with rising per capita incomes (they generally decline for food commodities as households become wealthier) also resulted in over-prediction of cropland conversion. Other possible misspecifications were shown to lead to underprediction of historical cropland expansion. In short, using a simpler model of global food systems allowed for insights into key economic mechanisms that were missing from the more complex models. Often such key assumptions are lost on the consumers (and producers) of results from large, detailed, interdisciplinary models. The SIMPLE model has also proved wellsuited to model validation exercises. Haqiqi et al.(2024) provide additional discussion of validation efforts for variants of the SIMPLE model.

Drawing inspiration from SIMPLE, the OECD constructed a long-term agricultural outlook (LAO) model with endogenous prcies to complement the price-exogenous AgLink baseline which is based on a reconciliation of national projections of the food economy (Saunders et al. 2019). As a consequence of endogenous TFP growth and the incorporation of long run supply response to prices, the LAO model projected lower agricultural prices than the AgLink baseline. The authors also note that this simpler framework could allow greater scope for systematic sensitivity analysis with respect to uncertain economic parameters, as demonstrated in Hertel et al. (2016).

Of course, there are sustainability challenges for which additional complexity is necessary. The debate over induced land use change associated with biofuel mandates is one such example. These indirect impacts – mediated through higher commodity prices -- were initially overlooked when the US mandates were put in place. It was not until an article appeared in *Science*, that this became a focal point of sustainability analyses (Searchinger et al. 2008). The initial work built on a relatively simple, partial equilibrium crop commodity modeling framework (Tokgoz et al. 2007). Due to the desire to regulate biofuels to ensure a favorable environmental outcome, considerable resources were directed towards the associated modeling, and the efforts became increasingly elaborate over time. Given the importance of international trade linkages, the geography of agricultural trade became a focal point, requiring more sophisticated modeling of bilateral trade flows (Villoria and Hertel 2011). Since ethanol production does not exhaust the feed value of maize, it was necessary to bring in models of biofuel byproducts and their use by the livestock industry, as well as trade in livestock products (Taheripour et al. 2010). In light of the potential substitutability of ethanol with petroleum in the fuel mix, and the volatility of global energy markets, it became necessary to consider the impact of mandates in the context of both high and low energy prices (Diffenbaugh et al. 2012). So, models of bioenergy also needed to cover energy markets (Serra and Zilberman 2013). More recently the aviation sector has become an important source of demand for biodiesel from soybeans. This has required expanding model coverage to the aviation sector (Zhao et al. 2021). In short, what started as a relatively straightforward, partial equilibrium, crop commodity modeling problem has evolved into a global multisector, general equilibrium modeling challenge. In retrospect, modelers might have been better off starting with a global general equilibrium model which accounted for all these linkages. Nonetheless, even if it strives to cover the entire economy, the models employed should be no more complex than needed to address the sustainability challenge at hand.

B. Simple Does Not Mean Unsophisticated

The sophistication in interdisciplinary sustainability analysis is not primarily about complexity of the economic model – which I will refer to as the "intensive margin of economics". It is about *applying established economic methods to new and difficult application domains*—what I would refer to as analysis at the "extensive margin" of our discipline. For example, when we started working with agronomists and ecologists on problems related to nitrogen fertilizer use, leaching and water quality, we realized we needed to bring to bear their knowledge of the fertilizer response of crop yields as well as the leaching propensity in specific locations, under a particular type of cultivation, accounting for local soils and weather conditions, into the economic model. We couldn't afford to rerun the full biophysical agroecosystem model every time we wanted to assess an economic policy. Accordingly, we needed to find a way of relating their site-specific yield relationships to the parameters in our constant elasticity of substitution crop production function. This required a two-step process. First, following an excellent proposal by one of our collaborators, Navin Ramankutty, we asked the agronomists to run their model dozens of times, varying the fertilizer application rates. Then we used these data to estimate the location- and practice-specific non-linear Gompertz functions characterizing the yield response to nitrogen. After this, we employed some creative economic-engineering to derive the relationship between the position, slope and curvature of the growth function for each site and the elasticity of substitution between nitrogen fertilizer and land (Liu et al. 2023). For the leaching relationships, we estimated location- and practice-specific quadratic leaching curves which could then be directly incorporated into the economic model, allowing us to readily read off the leaching outcomes for each policy scenario. This model allowed us to explore the impacts both of in-field interventions (e.g., a fertilizer tax, as well as mandating slower release fertilizers) as well as edge-of-field practices, including controlled drainage and wetland restoration (Liu et al. 2023). By reflecting the spatial, temporal and practice-specific elements of the agroecosystem model, we gained credibility with our interdisciplinary collaborators, enabling a wide range of valuable applications (Zuidema et al. 2023). It was also interesting to see that the agronomists and ecologists themselves found these simplified relationships to be informative. Another example of the value of simplicity!

III. Going Granular: The Spatial Imperative

A. The Geospatial Data Revolution—and Economists' Slow Uptake

The foregoing example of focusing on nitrogen fertilizer use and water quality highlights the need for high spatial resolution. The fertilizer-yield response and leaching curves in the preceding study vary according to cropping practices, soils, topography and weather. It is meaningless to ask such curves to represent conditions at the state or national level. Fine-scale analysis is essential for meaningful contributions to this important sustainability challenge. The first agricultural economist to pioneer global gridded analysis of climate and sustainability challenges was Hermann Lotze-Campen, who led the development of the MAgPIE model at the Potsdam Institute for Climate (PIK) (Lotze-Campen et al. 2006). This model has been widely used over the past two decades to assess alternative sustainability pathways for the food system (Bodirsky et al. 2025). In a similar vein, the global gridded GLOBIOM model developed at IIASA has been also been used in many sustainability studies (Valin et al. 2013; Havlik et al. 2013)

But what scale is appropriate? The MAgPIE and GLOBIOM models found themselves constrained by computational and data limitations so their grid cells were rather aggregated (at least compared to many of the studies of biodiversity and water issues cited here). However, the appropriate scale will vary according to the problem being analyzed as well as the availability of data and particularly the level of resolution employed by the biophysical members of the team. Economists working on global sustainability issues in collaboration with biophysical scientists must seek research partners who assemble data sets and calibrate their gridded models at broader scale than many of their biophysical research colleagues who are focused on individual locations. This has led the SIMPLE-G team to work at the level of 5 arc-minute grid cells (roughly 10km x 10km at the equator, and about 8km square in the Midwestern US). Accordingly, the SIMPLE-G-US crop model has more than 75,000 grid cells (Baldos et al. 2020) -- all connected through factor and product markets. In bringing the SIMPLE production structure down to the grid cell – hence the name 'SIMPLE-G' -- we have been able to parameterize the gridded production functions with information from our biophysical scientist collaborators who are also working at this same scale. Some variants of SIMPLE-G focus on a single country, nested within the global SIMPLE framework. For example, SIMPLE-G-US breaks out US agriculture at the grid cell but leaves the rest of the world aggregated into sixteen regions. Other variants of SIMPLE-G disaggregate the entire world at the level of individual grid cells (Haqiqi and Hertel 2025). Taking advantage of the model structure as well as specialized software for solving large scale equilibrium problems (Harrison and Pearson 1996), this model solves in minutes on a laptop (Baldos et al. 2020).

The first SIMPLE-G application was based on a collaboration with colleagues from hydrology (Liu et al. 2017). These collaborators had developed a global, gridded hydrological model, dubbed WBM (Water Balance Model). Like SIMPLE-G, WBM is a stripped-down model which only includes features essential for tracking the broad elements of the hydrological system. As with SIMPLE-G, WBM operates at 5 arc-minute resolution. We focused our attention on alternative solutions to unsustainable irrigation withdrawals across the globe and their impact on croplands and food security, including: (a) boosting productivity growth in irrigated areas, (b) investing in inter-basin water transfers and (c) liberalizing agricultural commodity trade. We were particularly pleased to be able to model the economic impacts of inter-basin water transfers by rewriting the supply-demand conditions governing water availability to encompass multiple watersheds, thereby allowing water to move amongst alternative uses across these connected watersheds. This got us thinking about other applications in which groups of grid cells become relevant units for such 'meso-level' analysis. Examples include labor markets (Ray et al. 2023) as well as regional commodity markets. In short, when you start your analysis at fine scale, 'the world is your oyster'! You can always aggregate up to a higher level, or group grid cells for purposes of representing local, as well as regional factor and commodity markets.

It is also possible to incorporate transport costs into this type of gridded framework. In an innovative application of SIMPLE-G-Brazil, Wang et al. (2024) analyze the impact of doubling the railway network in Brazil, as per a recent national infrastructure proposal for implementation by the year 2035. To undertake this analysis, the lead author first gathered data on transport ‘frictions’ between each agricultural grid cell and the major seaports of Brazil. When combined with private sector data on the cost of transport, Zhan Wang was able to introduce bilateral transport costs from each grid cell to the most accessible seaport, by road and/or rail. The authors then use SIMPLE-G Brazil to explore the implications of reducing these costs in line with the proposed infrastructure expansion. By reducing the transport margins to world markets, the enhanced infrastructure boosts farmgate prices - particularly in the middle of the country where access to railway lines is currently limited. What was particularly surprising to us was the degree to which the pattern of cropland use in Brazil shifts as a consequence of the changing pattern of comparative advantage. Cropland declines in the Southeast of Brazil, which currently benefits from ready access to ports, while it expands strongly in Mato Grosso and the Cerrado region of Brazil which currently rely heavily on costly road transport to get their products to the port. The ultimate consequence for carbon emissions depends critically on what happens to the abandoned cropland in the Southeast. Surprisingly, there are plausible scenarios in which total CO2 emissions in Brazil fall due to reduced transport-related emissions (following the shift from truck to rail) as well as cropland reversion in the Southeast of Brazil.

At global scale, one of the most difficult sustainability challenges facing the planet is the introduction of reactive nitrogen into the environment. Most of this stems from excess fertilizer use in agriculture (Richardson et al. 2023; Galloway et al. 2003). This is a problem which biophysical scientists have been working on at global scale for the past two decades (Gerten et al. 2020; Mueller et al. 2017). These scientists have pointed out that, by reallocating nitrogen fertilizer from the areas of overuse to regions where insufficient nutrients are being applied to crops, it would be possible to feed the world without excessive pollution of the environment (Smerald et al. 2023). However, despite the compelling narrative, this finding has not had an impact on policy.

The reason is, of course, that sustainability scientists are not the ones deciding where, when, and how fertilizer is applied to crops! Rather, this is the consequence of hundreds of millions of farmers making individual decisions about application rates, based on markets as well as individual preferences. The challenge is therefore one of formulating policies that will guide farmers to make decisions that are more beneficial for society as a whole. In short, there is a need for economic modeling of this sustainability challenge. However, due to the interconnected nature of global agriculture, this modeling cannot be done solely at the local level. Furthermore, an economic model operating at the regional or national level will not be meaningful, given the location-specific nature of yield and leaching relationships (recall the earlier discussion).

This sustainability challenge presented an ideal opportunity for implementation of a global version of SIMPLE-G. Building on a brainstorming session with Dieter Gerten, author of one of the earlier, biophysically based, global applications, we decided to embark on an interdisciplinary collaboration. This was inspired by our prior collaboration with Chris Kucharik's team and the AgroIBIS model of US midwestern agriculture (Kucharik 2003). But this time we aimed to build into global SIMPLE-G the location-specific, non-linear fertilizer yield response (Gompertz) and leaching curves implied by the global LPJmL agroecosystem model (Schaphoff et al. 2018). There were many challenges in executing this project. It required several years of effort and many iterations between the lead author, Iman Haqiqi, and the collaborating scientists at the Potsdam Institute for Climate Change Research (PIK). However, the resulting framework has generated important new insights (Haqiqi et al. 2025).

We began by calculating the local tax on nitrogen fertilizer that is required in order to bring nitrate concentrations in grid cell runoff down to a safe level (2mg/liter in this case). This varies widely, depending on current application rates, as well as local agroecological conditions. We then investigate the spatial impacts of such a regulation. Unsurprisingly to economists, there are market-mediated spillover effects, resulting in increased fertilizer applications at unconstrained locations. The extent of these spillovers depends on the elasticities of supply and demand. The latter are tied to the underlying yield response functions (and hence the elasticity of substitution between nitrogen fertilizer and land). However, the elasticity of fertilizer supply required further investigation. Lead author Iman Haqiqi undertook a variety of statistical exercises which revealed that N fertilizer supply tends to be driven by energy availability and production capacity with relatively limited own-price response – at least in the near term. Using his base value supply elasticity estimate (0.05), he finds that the decline in the price of nitrogen fertilizer, in the wake of a global regulation of its use, is sufficient to cause global crop production to increase. The finding that a tax on fertilizer use in agriculture boosts global output was initially counterintuitive to us. However, deeper investigation revealed that this was due to the non-linear nature of the Gompertz (yield response) and leaching curves. At high levels of fertilizer application, the marginal productivity of N is quite small, whereas the incremental addition to leaching rates if quite high. In contrast, at low levels of N applications, the marginal productivity is very high and the contribution to leaching is low. When environmental regulation induces a reallocation of N from the former to the latter locations, global production rises. Of course, this effect is moderated as the N supply elasticity increases. In the limit (perfectly elastic supply), the price does not decline and no such reallocation occurs.

Another important discovery facilitated by SIMPLE-G bears on the food security impacts of a global groundwater sustainability policy. Before tackling this question, the received wisdom in this field was established by hydrologists who predicted massive food insecurity if excessive groundwater use was curtailed (Famiglietti 2014). The version of global SIMPLE-G developed for this study built in data and parameters from the WBM global hydrological model, including estimates of unsustainable groundwater use at 5 arc-min. globally. This analysis confirmed that, if no economic adaptation were allowed, and unsustainable groundwater use were curtailed, global crop production would fall by more than 12% and food prices would skyrocket. However, by implementing this sustainability policy in SIMPLE-G, we were able to introduce economic adaptations to the ensuing scarcity. This includes on-farm adaptations (e.g., use of surface water instead, investments in improved irrigation efficiency), the possibility of reversion of some irrigated crop production to rainfed agriculture – albeit at lower yield, the relocation of crop production within a country, and finally, international trade, with water deficit countries importing food from water surplus locations. Once all these mechanisms were permitted to operate, the resulting global decline in food production is less than one percent. This was a revelation to the hydrologists with whom we were collaborating, and shifted the conversation from global impacts on food security to the local consequences for employment and farm incomes, which can be quite significant as crop production shifts geographic locations (Ray et al. 2023).

IV. The Global-Local-Global Framework: A Synthesizing Architecture

A. The Core Logic

Based on the foregoing examples of sustainability analysis in the context of nitrate pollution and groundwater depletion, it is clear that local conditions are key to understanding the impacts of sustainability policy interventions. Whether it is biophysical variation across the landscape, or differences in local governance, sustainability analysis is inherently local in nature. Nowhere is this more evident than in climate impact analysis where differences in temperature, precipitation, soils, topography, infrastructure and the extent of mechanization all play a role in mediating the impacts of climate change on the food system. Local sustainability stresses, and the capability of communities to respond to these challenges vary greatly across the landscape. However, the drivers of these sustainability stresses are typically global in nature. Beyond climate change, ongoing population and income growth, trade policies, disease and other broad scale factors drive local production decisions. Hence the need for global to local connections. These have been most fully developed by the climate integrated assessment community, which has a rich set of protocols for generating global scenarios, dubbed Shared Socio-economic Pathways (Doelman et al. 2018), and teasing out their local impacts (IPCC 2014). However, what has been missing to date is attention to the market-mediated spillovers from local to regional and global levels, as illustrated in the nitrogen, hydrology and transport infrastructure examples discussed earlier. Hence the call for new efforts in the field of Global-Local-Global (GLG) analysis of sustainability policies (Hertel et al. 2023).

One of the most compelling illustrations of GLG analysis is offered by Haqiqi et al. (2023) who decompose the drivers behind unsustainable groundwater withdrawals in the Western US. They show that the most important drivers are not those originating in the US, rather the most important are income and population growth overseas. Furthermore, when those authors implement, in a SIMPLE-G model, a groundwater sustainability policy in the Western US, the consequences for agricultural production elsewhere are significant, with cropland expanding in the Eastern US as well as overseas. This results in a significant net increase in global cropland area due to the very high yields in the irrigated areas where production is curtailed (e.g., California's Central Valley). Clearly this is a case where market-mediated spillovers from local sustainability policies are significant.

In some cases, fully capturing the spillovers may require embedding the gridded analysis within a broader modeling framework. Zhan Wang (2024) shows how this can be done for the case of Brazil, using the GTAP global general equilibrium framework. Previous extensions of the GTAP model to deal with land use have employed the GTAP-AEZ model which has 18 potential (non-contiguous) agro-ecological zones in each country (Hertel et al. 2008). However, Wang's GTAP-SIMPLE-G implementation incorporates individual crop production functions in each 5-arc-min. grid cell. By embedding this in the GTAP framework, he was able to shed light on the disaggregated land use impacts, within Brazil, of the US-China trade war. Embedding SIMPLE-G into the GTAP framework borders on violating the 'keep it simple' mantra developed above, but there are cases where this is essential to answering pressing trade and sustainability questions arising in the current global economy.

In summary, the GLG approach to sustainability science resolves the tension between the need for locally grounded analysis and globally relevant conclusions. It also creates a natural division of labor in interdisciplinary teams, with some of the team members focusing on model parameterization at the grid cell and others emphasizing the broader economic drivers and market-mediated spillovers. Importantly, it positions economists as integrators across scales

V. Leading from the Front: Economics as Organizing Framework

A. The Problem of Late Entry

A common pattern of interdisciplinary collaboration in the sustainability sciences is one in which the biophysical scientists frame the research question and identify the funding opportunity (grants are invariably more generous in the biophysical sciences), and, at some point, questions of policy arise. What are the costs and benefits of the proposed actions? Accordingly, an economist is recruited to address these issues. At worst, we are treated as 'bean-counters'. At best, we are asked to think about policy implications of scenarios that we did not ourselves help to craft. If the project is not initially built around an economic framework, this can make it very hard for the economists to make a meaningful contribution.

I would argue that the greatest value of economists in large, interdisciplinary projects is in their role as integrators. By starting out with an overarching economic framework, we can position the project to address economic policies aimed at solving the underlying sustainability challenges. Economists can be ideal Principal Investigators for these projects. Unfortunately, our training, as well as the underlying incentives systems for promotion in many agricultural and applied economics departments, do not position us favorably for such a role. I vividly recall a conversation with the US National Science Foundation Leadership for the INFEWS (Food-Energy-Water Systems) program in which they lamented the lack of economics-led proposals to this program. INFEWS awarded several hundred million dollars in grants, with very few being led by economists. This was a missed opportunity for many agricultural and environmental economists working on the food-energy-water nexus. The bulk of the proposals were led by hydrologists and biophysical scientists. As a result, they often failed to generate meaningful actionable, policy-relevant findings.

B. The Alternative: Economist-Led Framing

When economists frame the research questions and lead the proposal writing, the entire project architecture shifts. This economic framing naturally incorporates human behavior and decision-making, policy mechanisms and incentives, as well as the welfare implications and distributional consequences of proposed interventions. This type of framing creates space for biophysical science to inform economic questions rather than the reverse. One might reasonably ask whether the biophysical scientists would agree to participation in an economist-led project. However, I have found that the biophysical scientists are happy to contribute to such a research proposal/project, provided that: (a) it is shown to be decision-relevant, (b) it does not trivialize their contributions, rather the PI must take their work seriously and highlight its centrality to the problem at hand, (c) every effort is made to employ creative approaches to incorporating needed complexity of the biophysical systems. Finally, it is important that economists not be too closely wedded to one specific model. Rather, they need to start with a flexible framework that can be readily adapted to the needs of the problem at hand.

Of course, there are always those biophysical scientists who are unwilling to sacrifice any of their disciplinary detail and complexity in pursuit of an integrative project. The PI needs to identify these individuals early in the proposal process and leave them off the final project, as they will derail the entire effort. Ideally, the PI has had an opportunity to work with, or at least interact with, these scientists in advance, thereby assessing their potential for such collaboration. Joint teaching can provide an excellent vehicle for doing so, as I will detail below.

C. The Cost of Absent Economics

As has already been noted above, there is a high cost to omitting economics from sustainability research design at the outset. The first-generation biofuel legislation in the US is perhaps the most striking example. By ignoring market-mediated impacts of the US corn ethanol program, the impact on land use change globally was wholly omitted from the initial sustainability assessments (Farrell et al. 2006). The voluminous research on induced land use change has been an attempt to remedy this deficiency (Khanna and Crago 2012). In a similar vein, the omission of economists from project leadership has also resulted in sustainability solutions that are devoid of practical recommendations (Smerald et al. 2023).

D. Economists and Tradeoffs

One of the most popular responses to economists' policy presentations is the retort: "Enough of the tradeoffs – let's look for the win-win solutions!" Sustainability scientists often treat economists' emphasis on trade-offs as a failure of imagination! However, in a world of scarce resources, trade-offs are a feature, not a bug. Figure 1 in Valin et al. (2021) documents the pervasive nature of trade-offs in the context of the UN Sustainable Development Goals wherein food security is treated as the focal point, surrounded by the 16 other SDGs. They use arrows to depict tradeoffs, with the width of each arrow indicating the strength of the relationship, i.e., the share of the other SDG targets that impinge on SDG2 (no hunger) and vice versa. They find that the most intense, high-risk tradeoffs are with SDGs 6 (clean water), 13 (climate action), 14 (life below water and 15 (life on land). However, there are tradeoffs, as well as some synergies, with virtually all of the UN-SDGs. Since feeding a more affluent global population will often require both more land and more intensive production, this will inevitably translate into less habitat and more pollution. Policy makers can manage these trade-offs intelligently. But they cannot wish them away.

VI. Practical Implications for Agricultural Economists

A. For Research Practice

There are several practical suggestions for agricultural economists interested in advancing sustainability science research that emerge from this discussion. First, it is worthwhile investing in human capital related to geospatial methods and data infrastructure. These are skills which are typically not taught in our graduate programs, but such courses are widely available across campus and there is nothing to stop faculty members from auditing these courses. Students at the undergraduate and graduate levels should be strongly encouraged to enroll in such courses as schedules permit.

A second point pertains to the cultivation of collaborative relationships with colleagues across the biophysical sciences. Here, there is a natural link to teaching. There is no better place to initiate research collaborations than in the classroom. Sharing syllabi and offering guest lectures invariably result in immediate and deep insights into the interests and methods of your colleagues in agronomy, animal science, climate science, engineering, hydrology and many other disciplines. Finding an individual with whom you 'click' in the classroom is an excellent way to foster productive interdisciplinary collaboration. This is also an opportunity to embrace methodological translation – making your research legible to non-economists.

A third point pertains to the potential for exploiting the vast amounts of farm-level economic data which have emerged in recent years. In his recent AES Presidential Address, Paul Wilson (Wilson 2026) highlights the rich array data sets and underscores their underutilization in current agricultural economics research. Merging these data sets with the gridded frameworks discussed above would allow for a much richer understanding of how environmental regulations will affect the farm economy and the food system more generally.

B. For Training the Next Generation

A core skill to be conveyed to the next generation of agricultural economists is that of communication across disciplinary boundaries – both verbally and in writing. This can be accomplished in many ways. Interdisciplinary courses and seminars offer useful exposure to other fields and diverse ways of approaching sustainability challenges. Some students might even pursue a minor in one of these fields, although it is often difficult to free up the necessary space in a student's plan of study.

Some universities have introduced interdisciplinary graduate programs in sustainability sciences or adjacent fields. There is little doubt that graduates from such programs become effective communicators across disciplines. However, they also risk suffering from professional identity crises, leaving them in a quandary when it comes to the job market, and potentially weakening their career progression. It is usually the case that when a colleague from another discipline is looking for a collaborator, they are *not* looking for someone who knows a little about a lot of fields. They are looking for a top-notch economist. We much teach the fundamentals of economic theory and applications deeply in our graduate programs. Therefore, I believe that the best approach to interdisciplinary graduate education is to encourage students to obtain a disciplinary PhD, while engaging in courses or research projects that expose students to other approaches and diverse ways of thinking about sustainability science. It is also important to continue to nurture students' interest in the big questions – the global challenges – even as even as they focus their research more narrowly.

My own experience in teaching for the sustainability sciences stems from an annual, interdisciplinary graduate course offered through the Agricultural Economics Department to roughly twenty students from across the entire campus (Hertel 2020). This course was the most energizing and satisfying course which I have taught over my four-decade career as a professor at Purdue University. The first half of the course introduces students to the SIMPLE modeling framework for assessing future food security and the environment. In parallel to the weekly economics-driven lab assignments, students attend guest lectures (45 minutes, often virtual) from top scientists across all the sustainability sciences, ranging from demography to ecology, agronomy, hydrology and political science, among others. Prior to each lecture, students are required to read two recent articles from the field – typically published in top interdisciplinary journals such as Science, Nature and PNAS. They must then post online two questions in advance of the lecture and two students are assigned the job of synthesizing these questions into a coherent question and answer session (lasting 30 minutes) which covers the topic from a range of diverse perspectives. During the first half of the semester, students decide on a class project using the SIMPLE model which they actively pursue in depth during the final 7 weeks of class, in parallel to continuing guest lectures. At the end of the semester students present their findings to the class and submit a written paper.

Many of the class participants have found that this course shaped their thinking about thesis topics. And I personally found that this experience has had a profound impact on my own research. For example, in the module on climate change and agriculture, after presenting our research summarizing the IPCC (AR5) summary of the impacts of climate on crop production, a student from climate science asked me: 'What about the workers in the field? Won't they be affected by heat stress?' This precipitated a decade-long collaboration between our research group in agricultural economics and students and faculty in climate science, focusing on the economic effects of human heat stress (Saeed et al. 2022; De Lima et al. 2021; Hertel and de Lima 2020). Similarly, a student project in nutrition led to a deep collaboration on obesity, health and food waste (Lopez Barrera and Hertel 2020; Lopez Barrera and Hertel 2023).

This interdisciplinary class also became an excellent recruiting ground for collaborators from other fields. I found that, after swapping syllabi, listening to their lecture, and observing how they responded to students, I was able to accurately assess whether a faculty member would be an effective collaborator on an interdisciplinary project. Indeed, the first major interdisciplinary grant which I obtained was staffed entirely by faculty lecturers from my graduate class! Nick-named GLASS: Global to Local Analysis of Systems Sustainability (https://glassnet.net), that project gave rise to more than a decade of subsequent collaborations on grants, conferences and publications. In short, don't overlook the opportunity presented by offering an interdisciplinary course on your campus!

VII. Conclusion: The Next Century

In summary, the field of agricultural economics is uniquely positioned at the intersection of the environment, food systems, and human behavior – an area where many of the sustainability challenges of the 21st century reside. However, to realize this potential, we will have to be assertive, stepping into leadership positions on projects, conferences and publications, helping to frame the questions and set the research agenda. The sustainability sciences need our involvement, but they need us engaged on terms that enable genuine integration, not as simple add-ons to existing projects and papers. Deep integration will require that we keep our economic models simple enough to enable collaboration across disciplines while also allowing ample room for innovation at the 'extensive margin' of economic analysis. In addition, we must meet biophysical scientists at their preferred level of geo-spatial resolution, and we must step forward and lead large, interdisciplinary projects.

In closing, I have found that the Global-Local-Global approach offers a useful way of framing many of the sustainability challenges facing the planet in the coming century. I encourage those of you who would like to learn more about this approach to sustainability science to visit the GLASSNET web site (https://glassnet.net). This interdisciplinary network of networks embodies many of the principles outlined above (Hertel et al. 2023) and members of the Agricultural Economics Society are most welcome to join GLASSNET and contribute to its ongoing activities.

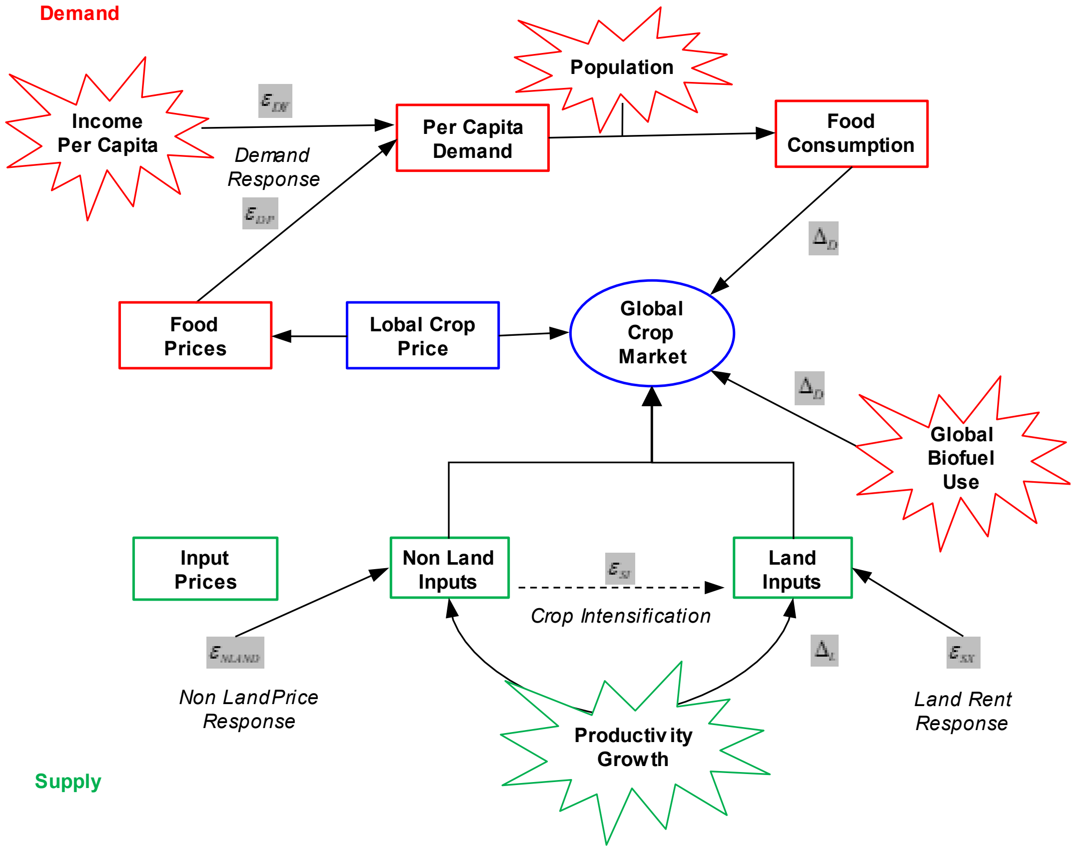

Figure 1. The SIMPLE Model. Red components denote demand considerations. Green components denote the supply side. Boxes are endogenous outcomes. Shaded boxes indicate economic parameters and perturbations to demand and supply.

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