Overview of Recent Developments in SIMPLE-G, a Framework for Multi-scale Analysis of Sustainability

Abstract:

Motivation: The world faces significant sustainability challenges in the decades ahead. Growing populations and rising incomes are placing unprecedented stresses on the planetary boundaries, with the world's land and water resources at growing risk (Steffen et al., 2015). The challenge posed in making such assessments is that sustainability stresses do not respect disciplinary boundaries. Furthermore, while the stresses are often highly localized, the drivers of these stresses are global, and the local responses can feedback to national and global outcomes. For this reason, assessment of the underlying risks, as well as potential solutions, is typically undertaken with a suite of models using complex approaches that often preclude replication and use by researchers outside the core group (Obersteiner et al., 2016; Springmann et al., 2018).

There are just a few open-source, bottom-up, economic-environmental modelling framework capable of analyzing global sustainability at the resolution of individual grid cells (Lotze-Campen et al., 2008; Valin et al., 2013). There is clearly a tradeoff between complexity and accessibility. Models used in teaching and academic research are generally simpler than those developed by national and international labs and research institutions. Having a relatively simple, global, grid-resolving sustainability framework that can be also run 'in-cloud' will allow wider participation in sustainability discussions and can facilitate greater crowd-sourcing of new ideas, data, and parameters to enrich the representation of local stresses, policies, and adaptations. The forthcoming book documents such a modelling framework -- SIMPLE-G, a Simplified International Model of agricultural Prices, Land use, and the Environment-Gridded version.

The SIMPLE-G framework allows for analysis of the interplay between economic and environmental systems, taking account of the actions of local agricultural producers pertaining to land and water use, within the context of regional and global commodity markets. This model integrates economic theories with environmental sciences to analyze the biophysical and economic impacts at different geospatial scales. The economic supply of land and water takes account of local institutions, biophysical characteristics, sustainability criteria, along with maximum available resources. As a consequence, heterogeneous local constraints lead to different rates of change in land and water use. On the demand side, growth in income and population lead to changes in food consumption baskets and changes in agricultural trade patterns.

Integrating the human and earth system analysis within a global economic framework is a challenging task and often focuses on one-way linkages, such as those used in down-scaling regional results to a grid cell level (Reilly et al., 2012). It has also been common practice to extrapolate from sophisticated grid-level analysis to national scale by assuming that the share of production or land use is unchanging (Schlenker and Roberts 2009). Bridging local, national, and global scales within a single framework is challenging, yet it is essential if we wish to bring into consideration the behavior of local decision makers within the context of global sustainability analysis. In the SIMPLE-G framework discussed in this paper, these decisions are endogenous to the model and take into account local biophysical characteristics and institutions as well as nationally determined input prices and globally determined commodity prices.

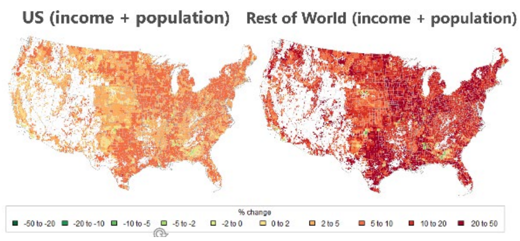
Links to Theory: An important feature of SIMPLE-G is its tight link to economic theory. This can be illustrated with a published example from the sustainability literature (Hertel, Ramankutty,

and Baldos 2014). The first relates to the debate over the impact of an improvement in agricultural technology on cropland use in the innovating region. Agricultural scientists have argued that 'doing more with less' and increasing crop yields is guaranteed to improve environmental quality in the innovating region (Borlaug Hypothesis). On the other hand, geographers have argued that, by making local agriculture more competitive, new technologies are guaranteed to lead to agricultural expansion and environmental degradation (Jevons' Paradox). The SIMPLE framework was used to reconcile these two divergent views. The following equation shows the percentage change in global land use in response to a one percent change in TFP in region A:

$$q_L^W / t^A = \delta(\nu_L^A / \theta_L^A)(\varepsilon_D^A - 1)/(\varepsilon_D^A + \varepsilon_S^A) + (1-\delta)(\nu_L^R / \theta_L^R)(-\varepsilon_S^A - 1)/(\varepsilon_D^A + \varepsilon_S^A)$$

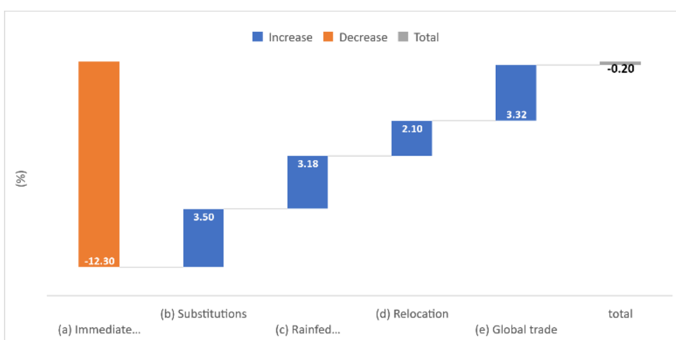
In this expression, δ denotes the share of global cropland area in region A, so ($1-\delta$) is the share of global cropland in RoW. Therefore, the percentage change in global land use is just a weighted combination of the change in land use in the two regions. As can be seen here, the *excess demand elasticity* facing region A: $\varepsilon_D^A = [\varepsilon_D^W + (1-\alpha)\varepsilon_S^R]/\alpha$ is a key parameter in the two-region model. It reflects the fact that the demand facing region A's suppliers is really a combination of the price responsiveness of world demand (ε_D^W) and supply response in the RoW (ε_S^R). In other words, when producers in region A become more productive and world prices fall, not only will global demand increase, but producers in RoW will reduce their production, thereby further accommodating the output expansion in region A. The slope of the excess demand curve depends critically on the relative share of region A in global production, parameterized here by α. As $\alpha \to 0$, as would be the case if A represented a single farm, the excess demand elasticity approaches infinity implying that a single farmer cannot influence world markets. This two-region analysis offers the following insight. From this expression, it is clear that Jevons' Paradox is an empirical matter. Depending on the parameters, either side of this debate may be correct. It depends on the specifics of the problem. This paradox is most likely to arise when: (a) global food demand is relatively elastic, (b) the innovating region covers a large share of global land area, (c) yields in the affected region are relatively low, (d) the cropland supply response in the innovating region is relatively large, and (e) the potential for substitution of non-land inputs for land in the rest of the world is large. Given this empirical ambiguity, the SIMPLE model was used to address this question with regard to the environmental impact of the historical Green Revolution. Hertel et al. (2014) demonstrate that, with 95% confidence (given parameter uncertainty), the Green Revolution was reduced land and carbon emissions globally, while possibly leading to increases in the innovating regions (confidence interval includes both negative and positive impacts on land use and emissions).

Global-to-Local-to-Global Analysis of Sustainability: The gridded version of SIMPLE, has now been used fairly extensively in collaborative research with physical scientists. Perhaps the most important insights to date in this work have related to the interplay between global drivers and local sustainability stresses and between local and regional policy interventions and global markets. These market responses convey price signals to non-targeted consumers and producers, thereby resulting in market-mediated spillovers from the local policies. We begin with an example from Haqiqi et al. (in review) which considers the impact of a groundwater sustainability in the Western United States. The authors use the subtotal feature of GEMPACK to decompose the impact of population and income growth across 17 world regions on local groundwater



withdrawals in the US. They show that the non-US drivers are much more important than those emanating from the national economy (see figure). In a second step, Haqiqi et al. explore the consequences of restricting groundwater withdrawals in each grid cell to a sustainable level (i.e., not more than the recharge rate). This is a local policy with global consequences, since many of the affected grid cells are extremely productive (i.e., high yields). The next figure shows the reallocation of production, both within the US and overseas. As a result of this local sustainability policy, total land use increases, both in the US and worldwide. The authors do not explore the impacts of these spillovers on groundwater sustainability outside the US, but it likely worsense the situation. Local policies have global spillover effects.

The Consequences of Ignoring Economic Adaptation to Policies: One way to limit advese spillover effects is to apply the policy globally. In a separate paper, Haqiqi, Perry and Hertel (2022) examine the consequences of a global groundwater sustainability policy using a global, gridded version of SIMPLE-G. The existing literature in the global hydrology community has been quite clear about the expected impacts on global food security (REFS). Due to the high productivity of groundwater irrigated agriculture, such a policy is expected to remove more than ten percent of global crop production from the market. Coupled with relatively price-inelastic food demand, this would result in massive price rises. The first (orange) bar in the adjacent figure shows the immediate impact on crop production worldwide, which falls by 12.3%. However, what the hydrologists have not considered are the farm, regional and global adaptations to this policy-induced scarcity of food. These include (moving from left to right in the figure): (i) farm level substitutions (increased use of surface water, enhanced irrigation efficiency, increased use of labor), (ii) reversion of irrigated land to rainfed production, where feasible, (iii) relocation of production within the region, and (iv) reallocation of production through global trade. Once these adaptations are taken into account, the equilibrium reduction in crop production is far smaller – just 0.2%! This comes as a shock to the hydrologists, and in response to their skepticism, Iman Haqiqi reran the model eliminating the on-farm substitution effects, to which the physical scientists objected. However, rather than sharply increasing the loss in global production, this model modification simply accentuated the other adaptations, with more relocation of production and a greater role for international trade. Ignoring economic adaptations greatly exaggerates the global cost of this sustainability policy.



In summary, by utilizing a rigorous approach to gridded economic modeling with minimal complexity, the SIMPLE-G framework allows for broad engagement with physical scientists and has generated useful insights for the global sustainability community.