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Economic Analysis of Global and Local Policies for Respecting Planetary Boundaries

Thomas W. Hertel[1]

1: Center for Global Trade Analysis Department of Agricultural Economics, Purdue University
Corresponding author email: hertel@purdue.edu

Abstract

In a series of highly cited papers over the period 2009 – 2023, earth system scientists have identified a set of nine planetary boundaries that must not be breached if we wish to avoid catastrophic consequences for nature and humanity. These range from well-mixed, global boundaries, such as climate-altering greenhouse gas emissions, to localized limits on freshwater availability and reactive nitrogen entering the environment. Recent estimates by Richardson et al. (2023), suggest that four of the nine planetary boundaries have already been breached. The food system is a key driver of all four exceedances and therefore must play a key role in any solutions. However, the establishment of these boundaries and the analysis of potential solutions has often been devoid of economic considerations. Furthermore, in the case of several of these planetary boundaries, limited attention has been given to the economic policies that might allow society to address them, as well as the likely synergies and tradeoffs across economic policies targeted to individual objectives. This paper seeks to bring further economic analysis to bear on the quantitative assessment of global and local economic policies aimed at respecting these planetary boundaries, concluding with six lessons to inform future research on this topic.

Keywords: Planetary Boundaries, agriculture, environment, tradeoffs, synergies, global trade

JEL Codes: Q00, Q01

Economic Analysis of Global and Local Policies for Respecting Planetary Boundaries

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*by Thomas W. Hertel**

Distinguished Professor and Executive Director, Center for Global Trade Analysis

Department of Agricultural Economics, Purdue University

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This paper focuses on the food system as a key driver of planetary boundary exceedances, as well as a source of sustainability solutions. Planetary boundaries are absolute limits on human-induced environmental pollutants which, if exceeded, will cause irreversible damage to the earth systems upon which we rely. The most recent assessment of these boundaries quantified nine such boundaries (Figure 1 from (Richardson et al. 2023)). Our food system currently accounts for one-third of greenhouse gas emissions (Crippa et al. 2021). It also results in land use change that is a key driver of tropical deforestation (Busch and Ferretti-Gallon 2017), which is, in turn, the main source of biodiversity loss on the planet (Leclère et al. 2020). Irrigated agriculture is also the most important user of freshwater and is a key driver behind groundwater depletion (Yoshihide Wada and Bierkens 2014). Finally, farming is the largest source of reactive nitrogen and phosphorous entering the environment (Gerten et al. 2020). In short, the food system plays a significant role in the exceedances of five of the six most problematic planetary boundaries identified in the most recent assessment. Furthermore, recent estimates suggest that developments in the global food system in the coming decades will only worsen these transgressions (Valin et al. 2021). In light of these heightened pressures, what can be done to lessen the adverse impacts of the food system on our environment?

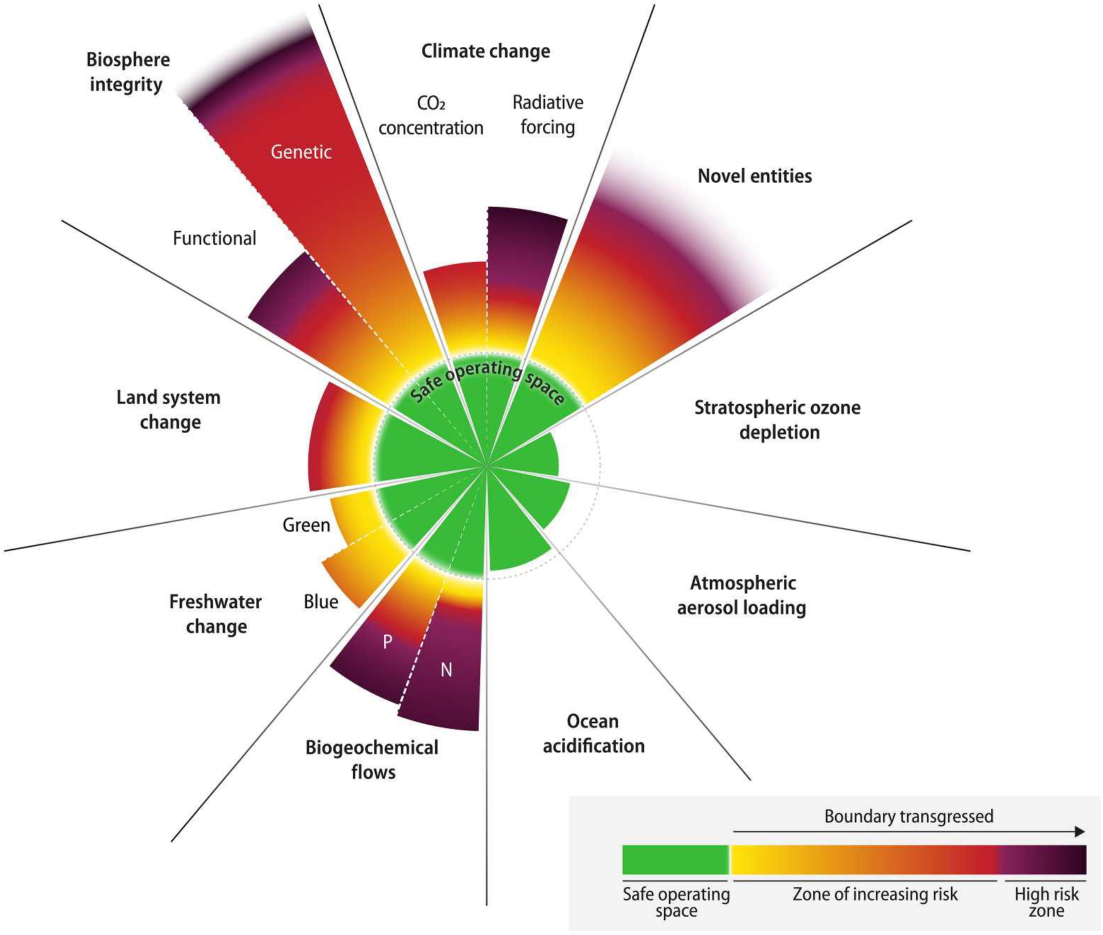


Figure 1. Planetary Boundaries (source: Richardson et al. 2023). Nine planetary boundaries and their current status. Green denotes safe operating space while purple shows most severe exceedances. Agriculture is a key driver of biogeochemical flows, freshwater use, land system change, biodiversity loss and climate change.

While local consumption of locally produced foods is a popular concept, today's food system is increasingly globalized. Supply chains now span national and continental boundaries. Global change drivers, including income, population, biofuels and technological change over the 2010-2050 period are projected to boost GHG emissions from the food system by more than one-third, increase nitrogen and phosphorous applications by as much as 50% and boost cropland and irrigation significantly as well (Valin et al., 2021). This translates into additional stress on the planetary boundaries in the absence of new and reformed policies. This paper will explore the impact of global food systems on four key planetary boundaries as well as potential solutions aimed at mitigating the environmental damages caused by agriculture.

Viewed through the lens of UN-FAO's recent State of Food and Agriculture report (FAO 2023), the aggregate cost of these environmental damages is large – amounting to roughly one-third of global agricultural value-added. These costs are proportionately highest in the low-income countries. That same report also seeks to quantify the true cost of the food system on human health, as conveyed through dietary choices. These costs are even higher. However, the present paper will not address the dietary dimension of the global food system, focusing instead solely on the environmental impacts. The paper concludes with six lessons for those seeking to bring economic insights to bear in future analyses of planetary boundaries.

Biodiversity and Ecosystem Services

From Figure 1, it is clear that one of the planetary boundaries most severely compromised is genetic biodiversity. Here, irreversible losses are accumulating at a rapid pace (Ceballos et al. 2015). It is estimated that, of an estimated 8 million animal and plant species on earth, roughly 1 million are threatened with extinction (IPBES, 2019), and roughly ten percent of genetic diversity has been lost over the past 150 years (Exposito-Alonso et al. 2022). In a seminal paper titled: "Bending the Curve of Terrestrial Biodiversity Needs an Integrated Strategy", Leclere et al. (2020) utilize a multi-model ensemble to highlight the crucial role of the food system and land use change in driving historical and future biodiversity loss. Under their business-as-usual scenario, they estimate that the world is currently on course to lose 13% of suitable habitat and 54% of wildlife density by 2100. However, they also identify a range of interventions which could contribute to reversing this trend or, in their terminology 'bending the curve' of biodiversity loss. These include supply side measures involving sustainable intensification of farming and increased agricultural trade, as well as demand side measures including reducing food waste and limiting animal product consumption. Finally, they explore conservation measures including extending protected areas, conservation planning and restoration of degraded habitats. When taken together, these ambitious changes to the food, and natural resource systems could reverse the downward trend in biodiversity.

Unlike some of the other planetary stresses (e.g., greenhouse gas emissions), biodiversity richness tends to be highly concentrated (Jenkins, Pimm, and Joppa 2013), and the threatened vertebrate species reside in a highly localized subset of these regions. Jenkins, Pimm and Joppa (2013) find that threatened birds are concentrated in the Andes and Southeast Brazil, along with Southeast Asian islands. Threatened mammals are most concentrated in Southeast Asia, while amphibians at risk of extinction are globally scattered, but highly localized. In short, *geography matters* when it comes to potential biodiversity losses. This has spawned a number of studies seeking to link growth in population and demand around the world to biodiversity via global supply chains. Lenzen et al. (2012) link animal species threats to land use, commodity production and international trade, and argue that 30% of threatened species are linked to trade. Chaudhary and Kastner (2016) undertake a similar exercise and conclude that 83% of total species loss is owed to conversion of natural lands to agriculture.

But how will these losses evolve in the future? Will the dramatic slowdown in population growth in many countries lessen this pressure for land conversion and biodiversity losses? Cisneros-Pineda et al. (2024) investigate this question using a global trade model (GTAP-AEZ) as modified for the study of biodiversity and ecosystem services (Johnson et al. 2023). They isolate the impact of population growth in each of 37 countries and regions of the world on land use change and biodiversity in every other region, measured as potential species loss. And this is done both for an historical period of demographic change (2001-2021) and a comparable future period (2021-2041). Pineda et al. (2024) find that the largest economic region in their model, the EU, will reverse the biodiversity impact it exerts on most other countries in the future, due to their population decline. China also shows a similar reversal with its population decline alleviating pressure on global biodiversity. However, demographic trends in other regions lead to heightened biodiversity stress, most notably Nigeria, Ethiopia and other countries in Sub-Saharan Africa (SSA). On net, despite the slowdown in the global population growth – and looming population declines in some of the richest nations – the future period does not show a declining rate of global biodiversity loss. However, the uncertainty associated with demographic change in the SSA region introduces enormous uncertainty into the estimates of future biodiversity losses.

While much of the literature on agriculture and biodiversity highlights the adverse impacts of the food system, there is another strand of research that focuses on the potential for biodiversity-agricultural production 'mutualism' (Seppelt et al. 2020). This captures the idea that ecosystem services, such as natural pollination and sediment retention, can enhance agricultural productivity.

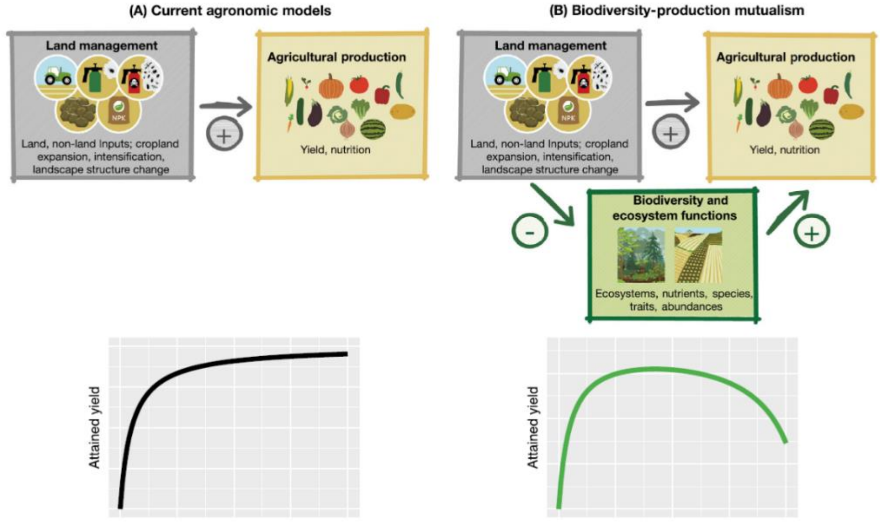


Figure 2. Contrasting traditional agronomic models with biodiversity-production mutualism. The mutualism model recognizes the connection between agricultural productivity and ecosystem functioning which may be jeopardized at high levels of intensification, thereby leading to yield declines. (Source: Seppelt et al., 2020)

However, these authors also make the point that ignoring this mutualism can lead to an adverse feedback loop wherein, for example, increased chemical use degrades the natural environment, leading to lower yields, therefore requiring additional cropland expansion, potentially leading to further intensification. The additional infringement on natural areas and associated ecosystem services can lead to further yield losses (Figure 2). The emerging field of agroecology aims to address this challenge by integrating the science of ecology with agricultural practice and societal values (Wezel et al. 2014). Agroecology seeks to maintain long term productivity while also limiting adverse environmental impacts (Gliessman 2015). To date, agroecology has been predominantly niche operations (Ewert, Baatz, and Finger 2023). However, this transdisciplinary, systems approach to studying agriculture is gaining significant traction – particularly in Europe -- where it is reshaping the way farmers and policy makers think about farming. The current challenge lies in integrating agroecological research with research on the broader food system and finding ways to scale up these technologies so that the benefits are more widely spread (Ewert, Baatz, and Finger 2023).

Closely related to the concept of biodiversity-production mutualism is the literature on more comprehensive measures of total factor productivity (TFP), often termed ‘Green TFP’ or ‘Total Resource Productivity’ (Fuglie et al. 2016; Ehui and Spencer 1993; Bureau and Antón 2022). which proposes to take agriculture-environment mutualism into account quantitatively by modifying TFP measures in such a way that pollution is treated as a negative output and common property resource extraction is counted as a costly input (Chambers 2016). This, more complete accounting of the environmental costs of new technologies, parallels the macroeconomic efforts to estimate ‘Green GDP’. Johnson et al. (2023) pick up on these ideas and develop a framework for linking economic and ecological outcomes in order to assess the economic benefits of environmental conservation aimed at enhancing natural capital. Their GTAP-InVEST modeling framework allows for analysis of the evolution of six different land-based ecosystem services alongside growth in the global economy. These include: sediment retention, pollination of crops, coastal protection, climate regulation, timber production and marine fisheries. The novelty in their analysis is that these ecosystem services, each measured using different ecosystem services models, evolve along their economic baseline (to 2021-2030 in this case) and feed back into the economic model via sector-specific productivity shocks (recall the mutualism idea in Figure 2). These authors find that, under a business-as-usual baseline estimated using the global economic model, the degradation of natural capital and associated ecosystem services, reduces global annual GDP by $US75 Billion in 2030. Importantly, the burden falls disproportionately on the world’s poorest countries.

Johnson et al. (2023) also explore potential conservation policies aimed at offsetting the ecosystem services degradation anticipated in their baseline simulation. They focus their attention on repurposing agricultural subsidies, investing the funds instead in nature-smart policies, including land rental payments for ecosystem services, and accelerated agricultural R&D. With these policies in place, they find that the GDP loss from degrading ecosystem services could be turned into a gain, ranging from $US 25-125 Billion in 2030. Furthermore, the gains would disproportionately benefit the lowest income countries. These results echo the findings of Gautam et al. (2022) who provide a more comprehensive analysis of repurposing agricultural support to achieve a more sustainable food system. They find that simple reductions in, or rearrangement of, current support are unlikely to yield significant environmental benefits. Instead, they too argue for investing these funds in the development and adoption of green innovations, in effect allowing farmers to ‘do more with less’.

The role of productivity in protecting the environment has been gaining increased attention (Coomes et al. 2019; Fuglie et al. 2022) and it is also the subject of a forthcoming OECD workshop. There is now substantial evidence that historical R&D investments, aimed at generating new crop varieties, has limited cropland expansion (Stevenson et al. 2012; Hertel, Ramankutty, and Baldos 2014; Villoria 2019). There is also emerging evidence that these benefits extend to limiting biodiversity loss – at least at the global scale. Baldos et al. (2024) assess the impact of the adoption of modern crop varieties (Fuglie and Echeverria 2024) on global croplands and biodiversity. While the global impact has been land-saving, the gridded analysis by Baldos et al. (2024) reveals that, at a local scale, the consequences of modern variety adoption has sometimes been cropland expansion (Figure 3). This arises when intense local adoption makes local producers relatively more competitive, relative to producers elsewhere (Jevons’ paradox). The impact of these new crop varieties on biodiversity depends critically on the gridded overlay of cropland change on these biodiversity hotspots. As with cropland extent, the introduction of the CGIAR-related modern crop varieties (Fuglie and Echeverria 2024) has been globally beneficial to biodiversity. However, in the hotspots of cropland expansion, including in southeastern Africa and Southeast Asia, Baldos et al. (2024) find that the introduction of these modern varieties has resulted in increased potential for species loss.

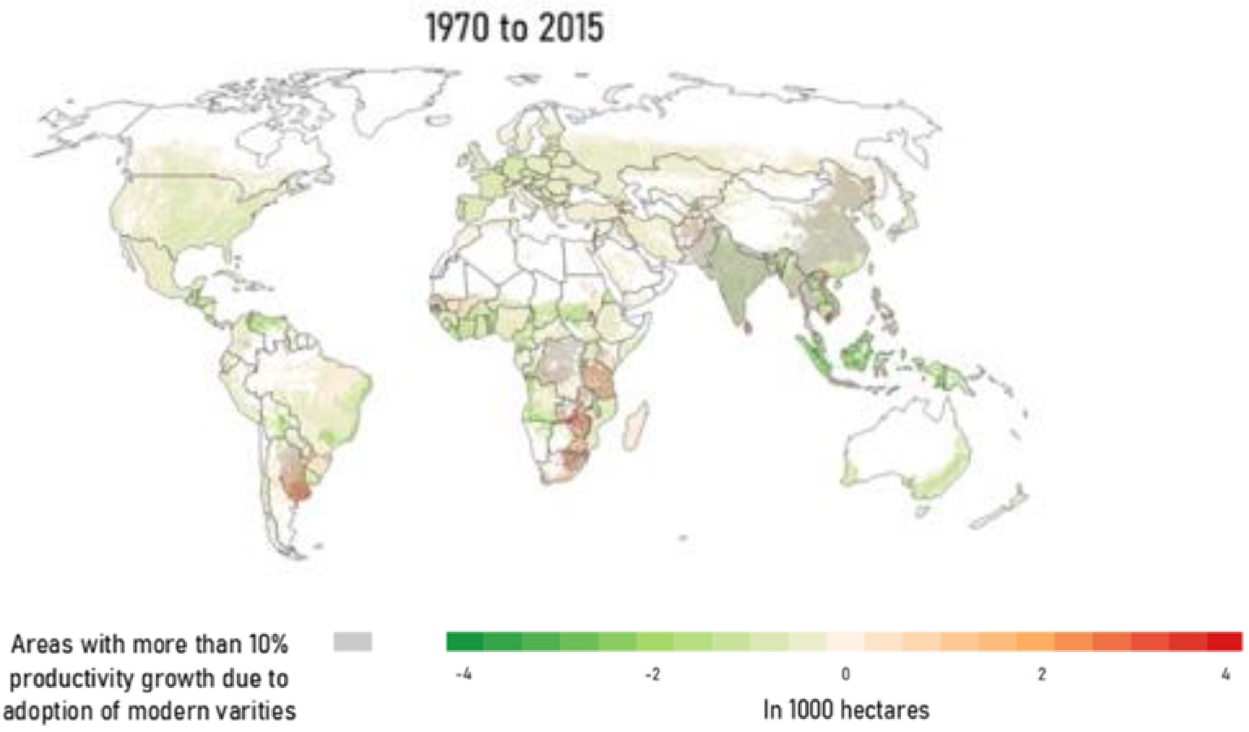
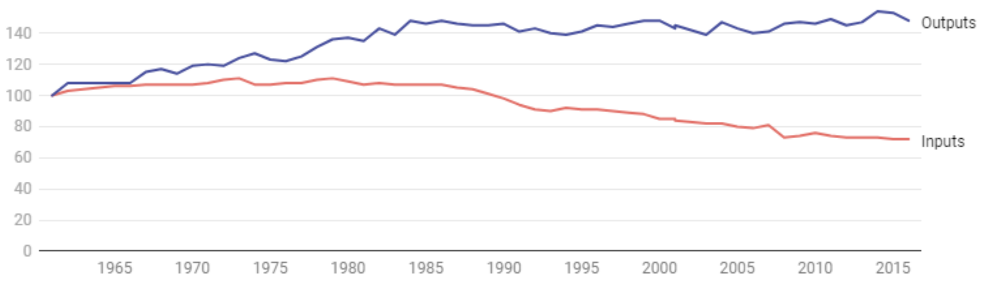


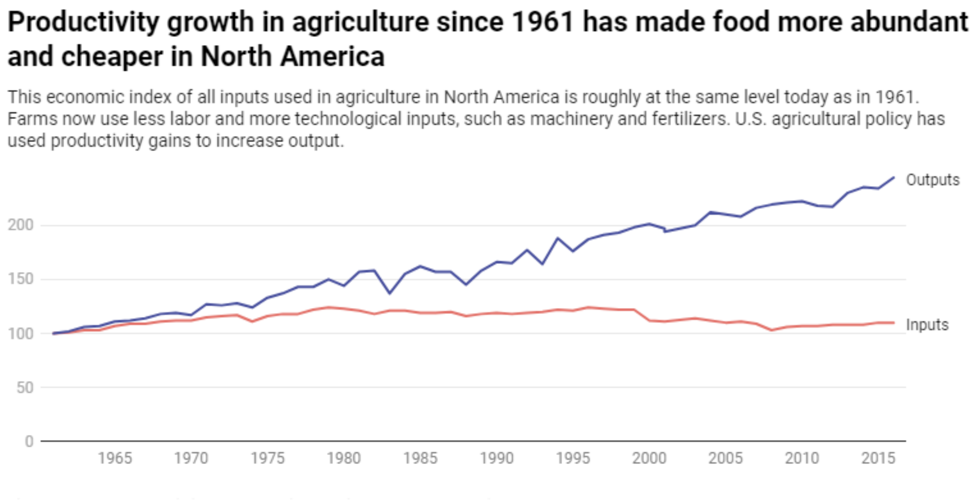
Figure 3. Change in cropland area due to the introduction of modern crop varieties: 1970-2015. Source: Baldos et al. 2024.

Rather than leveraging productivity growth to expand production, some high income countries have taken advantage of TFP improvements to withdraw resources from agriculture, in favor of the environment (Heisey and Fuglie 2018). Nowhere is this more evident than Northwest Europe, where there is a strong emphasis on agri-environmental policies (Wuepper et al. 2024). Restrictions on fertilizer and chemical use, as well as limits on animal numbers and cropland extent, along with reforms to the Common Agricultural Policy, have resulted in a secular decline in input usage in agriculture (Figure 4a) (Heisey and Fuglie 2018). Nonetheless, strong TFP growth has permitted this region to maintain agricultural output over this entire period (Figure 4a). This contrasts sharply with the pattern of input usage in US agriculture (Figure 4b), where the index of aggregate inputs has remained virtually unchanged over the past 50 years. Instead, reduced land and labor have been offset by increased spending on machinery and intermediate inputs such as seed and chemicals (Heisey and Fuglie 2018). As a result, strong TFP growth has been the dominant explanatory variable behind continuing farm output growth in the US. This implicit choice of 'how to use TFP growth' is largely a political decision – weighing the tradeoff between agricultural and environmental interests. In the EU, this tradeoff has clearly tilted in favor of the environment as reflected in the large number and intensity of environmental policies directed at the farm sector (Wuepper et al. 2024).

Northwest Europe has reduced farm inputs without sacrificing food production

Farms in Northwest Europe use fewer inputs than they did in the 1960s and 1970s, particularly land, but strong productivity growth has enabled them to produce a consistent amount of food. These nations' agricultural policies emphasize conserving resources without reducing output.





Productivity growth in agriculture since 1961 has made food more abundant and cheaper in North America

This economic index of all inputs used in agriculture in North America is roughly at the same level today as in 1961. Farms now use less labor and more technological inputs, such as machinery and fertilizers. U.S. agricultural policy has used productivity gains to increase output.

Figure 4. Top Figure (4a) shows input and output growth in Northern Europe. The difference between the two lines is attributable to Total Factor Productivity (TFP) growth. Figure 4b shows comparable time series for North America. Source: data taken from Heisey and Fuglie (2018) as presented in Hertel (2021).

There are strengthening calls, worldwide, to set aside more land for nature (IPBES Secretariat 2019). Dubbed *’30 by 30’*, the broad thrust of the most recent IPBES proposal is to set aside 30% of the earth’s land and oceans for nature, by the year 2030 (Dinerstein et al. 2019). The precise details of where and how this would be achieved remain to be worked out, but given the ambition of these proposals, they will clearly have an impact on agricultural land use. In earlier work, Mehrabi, Ellis and Ramankutty (2018) estimated that setting aside half the earth’s surface for nature would reduce cropland area by 15-31%, pastureland by 23-25% and crop calorie availability by 3-29%. However, in addition to exploring a more ambitious target, their analysis did not factor in economic responses to the measures. Above all, most analyses to date have not considered how such a policy would be implemented. Would the land simply be set aside as a national or international park? Or would the policy be voluntary, with market incentives to set aside biodiversity-rich lands in sensitive regions? Would the market incentives involve taxes on the conversion of natural lands, or would it involve subsidies to restore commercial lands to their natural state? Would such subsidies vary with the agricultural productivity of the land being set-aside? Will there be a priority placed on agriculture-biodiversity mutualism? What metric for biodiversity would be employed? Would the policy be implemented at the local, regional or national scale? Given the local nature of biodiversity hotspots, how would the effectiveness of the policy be reduced if the policy is implemented at the national, as opposed to local, scale? There are many practical questions that have not yet been addressed. Yet these have important implications for the impact which 30x30 will have on the food system.

In ongoing research on this topic, Haqiqi et al. (in Review) explore the potential economic impact of a global 30x30 policy which seeks to set aside biodiverse lands currently under cultivation, and protect biodiverse lands that are under natural cover. Using a spatially resolved land allocation model, they estimate that conserving 10 million km² of land would cost between $71 and $120 billion USD. This translates to an average cost of $71 to $122 per hectare, with significant spatial variability due to differing opportunity costs of land across locations. In China and Japan, conserving land may require up to $500 per ha for highly profitable cropland. In Brazil and Sub-Saharan Africa this can be as low as $27 per ha. They find that the impact of this policy on global food production is surprisingly small (~ -2%) due to market adjustments and spillover effects.

Barbier and Burgess (2019) make the argument that establishing such absolute limits on land use is a necessary condition, but it is not sufficient for achieving the stated goal of preserving biodiversity and keeping the world within a safe operating zone. The problem is that the *absolute scarcity* of land induced by such policies will raise land rents and make the ultimate goal more difficult to achieve. They argue that landowners will be encouraged to convert all of those areas outside this narrow limit, thereby accelerating the loss of ecosystem services. Instead, these authors argue that the core of the problem rests with the undervaluation of, and underinvestment in, natural ecosystems. They argue for *managing relative scarcity* by boosting the cost of eroding ecosystem services, thereby sending economic signals to decision makers to make better use of this natural capital. They provide an illustrative example of this challenge for the case of natural forests. Here, they conclude that cutting in half the rate of tropical deforestation without changing the economic policy environment would only extend the lifetime of the remaining safe operating space for these forests from 11 to 21 years. In contrast, an optimal economic policy aimed at raising the relative scarcity of these forests would treat the remaining safe operating space as a depletable resource which should be managed via a time varying tax on deforestation. They find that such an economics-based policy would greatly reduce the rate of depletion of the remaining safe operating space and extend the lifetime of this asset – potentially for as much as 200 years.

In a more in-depth case study of ecosystem protection, Barbier and Burgess (2024) explore these issues in the context of a case study of the attempts to preserve the world's peatlands. Peatlands comprise plant materials which have been partially decayed and accumulated over a long time period. While peatlands cover just 3% of the terrestrial planet (Humpenöder et al. 2020), they have been estimated to store twice as much carbon as all of the world's forests (Yu et al. 2010). Peatlands also provide a wide range of other ecosystem services ranging from the provision of unique habitat, supporting water cycles and filtering pollutants. Yet, despite these many contributions, peatlands are being rapidly drained and degraded. Barbier and Burgess (2024) point to the current mismanagement of these peatlands, arguing that they are fundamentally undervalued, with subsidies to agriculture, forestry and mining often resulting in accelerated drainage and degradation of this natural resource. They recommend that countries with significant peatland areas should ensure that the services provided by these natural ecosystems are taken into account by those making land use decisions. Their second recommendation involves boosting technical and financial assistance for countries seeking to invest in their peatlands – not only protecting existing peatlands, but also 'rewetting' drained peatlands so they can be restored to their natural state. While costly, this can be an important part of a global climate mitigation strategy (Humpenöder et al. 2020), a topic to which we now turn.

Climate Change

When the term planetary boundary is mentioned, most scientists, as well as members of the public, are inclined to immediately think about climate change and the seemingly inexorable rise in greenhouse gas concentrations in the earth's atmosphere. In addition to the steady increases in global mean temperature, climate scientists have made great progress in the field of event attribution, linking some of the extreme events involving flooding, drought and severe storms to the rise in GHG concentrations in the atmosphere (Otto 2017). These concentrations have risen from about 277ppm in 1750 to 420ppm today (US Department of Commerce). Since CO2 is a well-mixed, global pollutant, it does not matter where the GHGs are emitted, they have the same impact across the entire planet. This creates unique opportunities from a mitigation policy perspective because it doesn't matter where the reduction in GHG emissions occurs. Therefore, the optimal global policy involves starting with the lowest cost mitigation options, worldwide. Of course, since many of these low-cost options are in the world's low-income countries, the question of who pays for the abatement is critical.

The idea of starting with the least cost GHG abatement is important for the food system, since the land-based abatement policies are often amongst the least cost options -- specifically those measures related to agriculture and forestry (Murray et al. 2005; A. Golub et al. 2009). McCarl and Schneider (2001) identify three different avenues through which agriculture can contribute to mitigating climate change: direct reduction in emissions (e.g., through manure management, modified fertilizer use, etc.), soil carbon sequestration and avoided deforestation, and through production of commodities that substitute for fossil fuels (e.g., biofuels). Virtually all of these mitigation policies lead to increased food prices which can have adverse consequences for the poor who spend a disproportionate share of their income on food (Golub et al. 2012; Hasegawa et al. 2018; Havlík et al. 2015) and these low income households benefit little from the expected scarcity-induced increases in land returns (Hussein, Hertel, and Golub 2013). When implemented at global scale, a carbon pricing scheme would also penalize agricultural activities in low income countries which are typically characterized by very high emissions per dollar of output (Avetisyan et al. 2011). In practice finding a policy combination that takes advantage of low cost mitigation options, while also avoiding deleterious effects in the poorest countries and households is a challenging task (Henderson et al. 2017). Furthermore, absent the capability of actually monitoring emissions from millions of farms to ensure that less emissions intensive practices are put in place, a carbon tax must essentially resort to reducing output of the polluting activities, which in turn raises food prices (Martin and Vos 2024).

An alternative to farm level regulation, taxes or other cost-increasing measures is to make public investments in new technologies that have the potential to increase output per unit input and therefore lower costs while also reducing GHG emissions for a given supply of food. These investments generate knowledge capital which raises productivity, not only in the country making the investment, but often in other countries -- through knowledge spillovers (Fuglie, 2018). There is a long tradition of studying the relationship between R&D and productivity in agricultural economics and the evidence is that these investments yield a high economic return (Alston et al. 2010). However, less attention has been given to the environmental impacts of such investments. Fuglie et al. (2022) argue that GHG emissions from agriculture are closely tied to total input use, and since historical investments in productivity-enhancing public R&D have limited the growth in agricultural inputs, they have also served to limit GHG emissions from agriculture. In considering a range of future investment scenarios, they argue that accelerated R&D investments could achieve abatement at a cost as low as $11/ton CO2e if combined with policies preventing agricultural conversion of carbon-rich natural lands. This compares very favorably with other mitigation options. Furthermore, unlike on-farm mitigation measures, the public R&D investment policy does not require regulatory compliance by hundreds of millions of individual farmers. Fuglie et al. (2024) provide a comprehensive review of agricultural productivity and its consequences for climate mitigation and conclude this avenue offers relatively low-cost mitigation (less than $50/ton CO2e). Furthermore, by targeting such investments to the more emissions-intensive commodities in agriculture, they argue that marginal abatement costs could be far lower than this estimate. This point is further developed by Gautam et al. (2022) who argue that green innovations should be specifically focused on methane-intensive production activities (rice and ruminants) where there appear to be significant opportunities for reducing emissions of the highly potent GHG while also improving productivity.

An additional benefit of the productivity-enhancement approach to GHG mitigation is that, when employed broadly, it lowers the cost of complementary policies aimed at removing ecosystem sensitive lands from production. By boosting output on existing agricultural lands, commodity prices are lowered, and land rents are also reduced, relative to baseline. Therefore, the subsidy required to prevent conversion of natural lands is also reduced. Fuglie et al. (2022) find that this policy synergy, between enhanced public R&D in agriculture, and the protection of carbon rich natural lands, results in a 10% reduction in the cost of implementing global land conservation. Martin and Vos (2024) also point out another benefit of the R&D-led approach to GHG mitigation: reduced leakage from country-specific investments as other countries are confronted with lower commodity prices as a result of the innovating region. This contrasts with a regulatory approach to limiting emissions, which raises prices and encourages production increases in more polluting regions.

There are additional co-benefits from climate mitigation policies – particularly reductions in fossil fuel combustion where significant health and environmental gains have been identified (Ürge-Vorsatz et al. 2014). However, apart from the extensive literature covering climate impacts and mitigation in agriculture, the interplay of climate policy, food systems, and other planetary boundaries has been less fully explored. In a recent study of climate policy in the US, Zuidema et al. (2023) uncover important water quality benefits from a carbon-based pricing scheme (Figure 5). The mechanism underlying this linkage is as follows. Carbon pricing raises the cost of carbon-intensive goods with the cost rising roughly in proportion to the cost share devoted to carbon-intensive inputs. Very few commodities are as carbon intensive as nitrogen fertilizer, where the cost share of natural gas in anhydrous ammonia (which serves both as a feedstock and as an energy source for the synthesis reaction in the Haber-Bosch process) is very significant. When evaluated at a social cost of carbon of $176/ton CO2e – the high end of current US estimates (U.S. Interagency Working Group 2021), Zuidema et al. (2023) estimate that natural gas costs would rise by 176% and anhydrous ammonia prices would nearly double. This, in turn, has a significant impact on nitrogen fertilizer applications in the US Corn Belt. Zuidema et al. (2023) predict that nitrogen fertilizer use would fall by about 14% -- half due to a reduction in corn production, and half due to reductions in application rates (Figure 5). With less nitrogen fertilizer being applied, there is less nitrate leaching. The authors estimate that this translates into about 8% less nitrate pollution going into the groundwater and with similar reduction in nitrate export to the Gulf of

Mexico. The smaller than proportional decline in nitrate exports stems from the natural ecological processes that occur between the runoff from a farmer's field and the ultimate delivery to the Gulf (Zuidema et al. 2024). Given the lack of success to date with voluntary programs aimed at reducing non-point source pollution from US agriculture, this is a significant impact. Indeed, Zuidema et al. (2023) estimate this reduction in nitrate exports to the Gulf of Mexico to comparable to, or even greater than, the gains offered by widely advocated wetlands restoration programs. In sum, these water quality improvements represent an important, positive synergy between the climate and biogeochemical planetary boundaries.

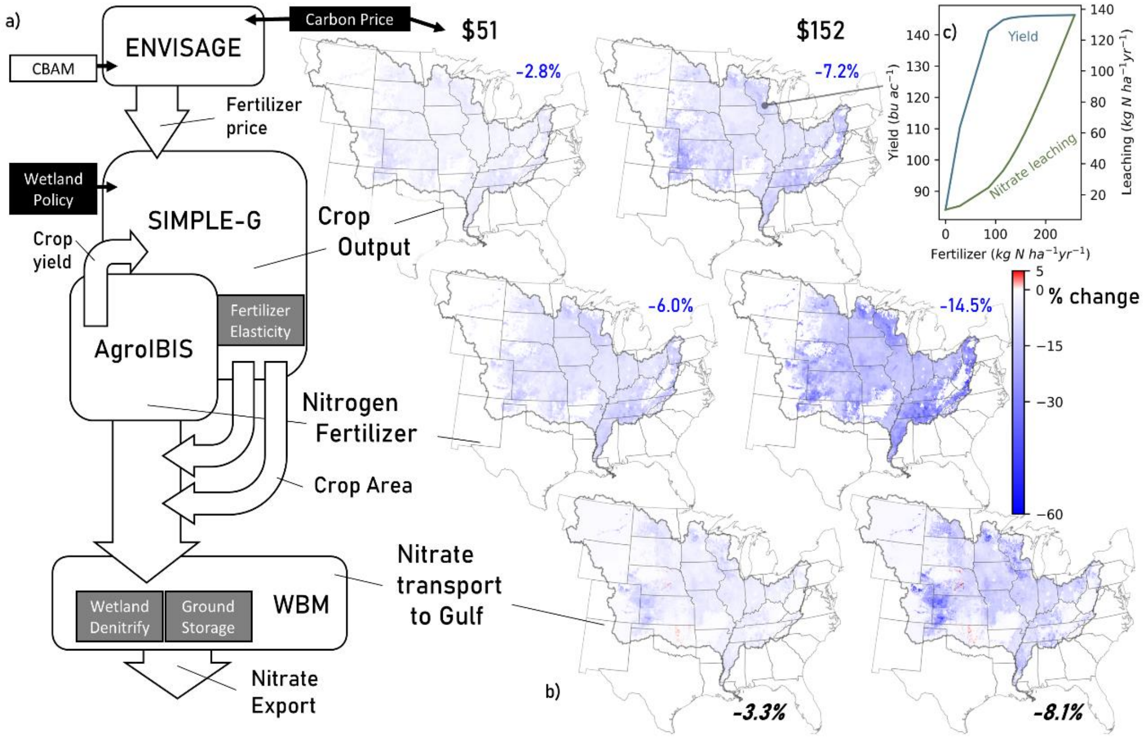


Figure 5. Cascading effects of US climate mitigation through carbon pricing at $51 and $152/tonne of CO2. Costly natural gas raises the price of nitrogen fertilizer and shifts the demand and supply curves for crop production (EVISAGE model). These effects are incorporated into the gridded SIMPLE-G model of corn and soy production, reducing nitrate leaching (Agro-IBIS model) and hence lowering pollution of ground and surface water. Discharge into the Gulf of Mexico falls by 8.1% at the high carbon price (Water Balance Model estimates). Source: Zuidema et al. (2023).

Water Quality

While there are potential synergies between climate policy and water quality, when viewed through the lens of planetary boundaries, it is the biogeochemical flows – in particular nitrogen (N) and phosphorous (P) – that present the more severe exceedances (Richardson et al. 2023). Furthermore, unlike climate change, these are not well-mixed, global pollutants, but rather they are the result of complex processes – often quite localized -- that are not always well understood or measured but which can have widespread impacts on the environment and human health (Vitousek et al. 1997; Galloway et al. 2003). There is a rich history of attempts to deal with N and P pollution at a local level through a variety of policies, including more efficient use of nutrients in-field, as well as edge of field mitigation policies (Iowa State University 2013). The most cost effective policy will inevitably depend on a whole host of considerations (Christianson, Tyndall, and Helmers 2013). A recent study by Liu et al. (2023) looks across the entire US Corn Belt, considering four different types of policies, including taxation tied to nitrate leaching rates, improvements in farm practices to increase nitrogen use efficiency, such as splitting applications, as well as controlled drainage, and wetland restoration. Those authors find that the most effective policy varies widely across the Corn Belt (Figure 6, left panel). Furthermore, they find that the wetlands policy, which is the most impactful overall, also has significant spillover effects (Figure 6, central panel) whereby the reduction in nitrate leaching in the areas targeted for restoration boosts prices and encourages increase nitrogen use elsewhere. However, these spillovers are eliminated when a region-wide policy, such as a leaching tax or the carbon pricing policy discussed above (Zuidema et al. 2023), is added to the mix. This is because the spillover locations are also given an incentive to reduce fertilizer application rates.

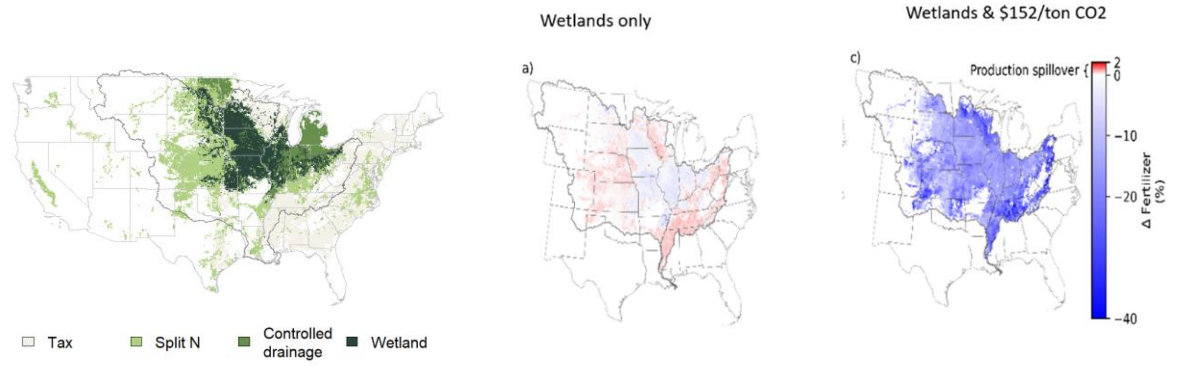


Figure 6. Impacts of alternative policies for reducing nitrate leaching in the US Corn Belt. Left hand panel shows the most effective policy for each grid cell, including taxation of leaching, most efficient nitrogen utilization through multiple applications, controlled drainage and wetland restoration. Middle panel shows how a wetlands policy operating in isolation generates spillovers in the form of increased fertilizer applications on the fringes of the Corn Belt. The right-hand panel shows how a national carbon price eliminates the spillover effects by raising the price of fertilizer for all producers.

These findings highlight the fact that, while water quality is a local problem, addressing it can have broader impacts – often conveyed through market mechanisms. This is particularly true when one considers potential solutions at global scale. Gerten et al. (2020) have suggested that a reallocation of nitrogen fertilizers globally could allow producers to feed the world adequately while respecting multiple planetary boundaries. Smerald et al. (2023) reach a similar conclusion, arguing that fertilizer use could be reduced by one-third, while maintaining global production of major cereals, simply by reallocating the global distribution of fertilizers. However, these authors do not propose specific policies to achieve this reallocation. Furthermore, they do not explore the potential economic impacts of achieving this goal. What would be the consequences for prices, employment and trade? In an effort to redress this limitation, Haqiqi et al. (2024) build on prior work by Schulte-Uebbing et al. (2022) which has quantified local planetary boundaries associated with nitrate pollution from agriculture. Instead of using a strictly biophysical modeling approach and dictating *a priori* how the nitrogen should be applied globally in order to return to a safe operating space (Gerten et al. 2020), Haqiqi et al. (2024) explore how alternative policies might guide the decentralized, global economy towards such a solution.

Haqiqi et al. (2024) pursue this investigation by embedding the underlying biophysical relationships between nitrogen applications, yields and leaching – derived from the LPJmL ecological model -- within a global, gridded economic model (SIMPLE-G). They follow a similar methodology to that used by Liu et al. (2023) for the case of the US. Haqiqi et al. (2024) evaluate the impacts of a location-specific tax aimed at curbing excess nitrogen applications. This approach yields some important insights about tradeoffs and synergies. Firstly, the reduction in fertilizer demand in locations where nitrate leaching is stressing the local environment, such as Northeast China, Northern Europe and the US Corn Belt, reduces the domestic prices of nitrogen fertilizer and encourages a reallocation of N within the national market (Figure 7). In addition, nitrogen fertilizer is widely traded and so the reduced demand in these countries makes fertilizer more affordable for producers in other regions of the world where application rates are currently very low, and the marginal productivity of fertilizer is very high, such as Africa and parts of South America. This, in turn, boosts local food production and enhances food security in those regions. In addition, higher fertilizer prices in Northeast China, Northern India, and parts of the US create incentives for production to move elsewhere. The consequences of these market forces are not dissimilar to the reallocation of fertilizer designed to minimize the environmental footprint postulated by Smerald et al. (2023) – although the magnitude of the reallocation is much smaller. The key difference between these two analyses is that the economic model predicts the reallocation due to market forces in response to a specific policy intervention, as opposed to determining this reallocation ‘from on high’ based purely on biophysical logic.

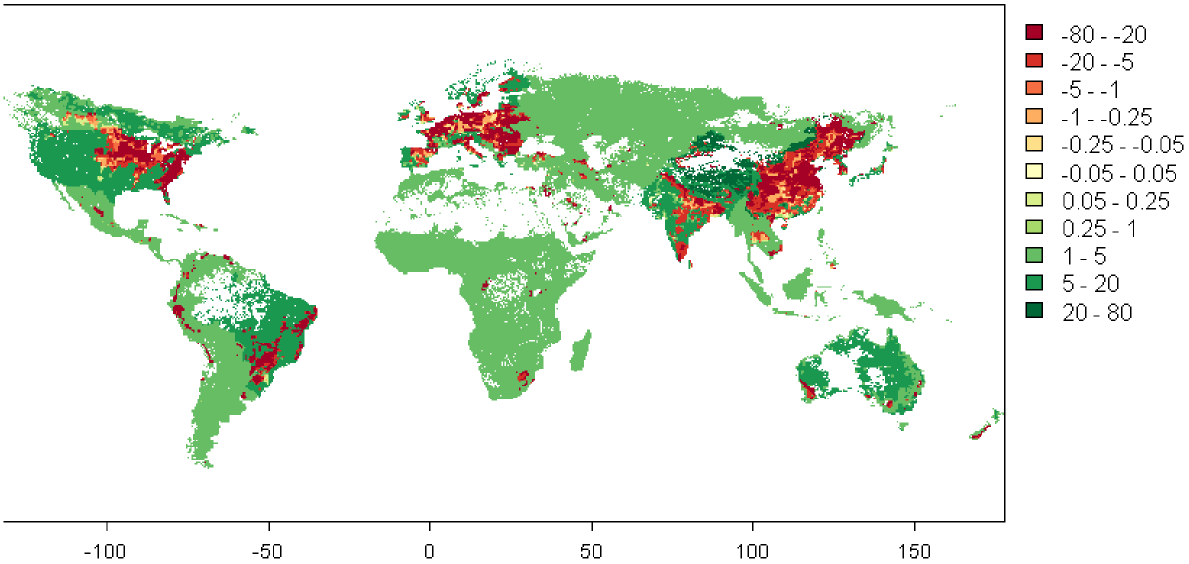


Figure 7. Percentage change in nitrogen fertilizer applications in the wake of a nitrate leaching tax in locations with planetary boundary exceedances. Green areas denote locations where market-mediated spillovers encourage additional applications. Source: Haqiqi et al. (2024).

Overall, Haqiqi et al. (2024) estimate that global cropland must increase by 0.1% or 1.6 Mha in non-target locations to partially compensate for the lower level of intensification in the regions of the world where nitrogen fertilizer is currently used in excess of the safe operating space. This is a planetary boundary tradeoff, as cropland expansion can lead to deforestation, the release of terrestrial carbon, and the loss of other natural ecosystem services. However, the coincidence of excess nitrogen applications with groundwater mining in some regions (e.g., Northern India), also generates positive planetary boundary synergies. In these regions, production and hence groundwater withdrawals are predicted to decline in the wake of more the costly nitrogen fertilizer input. So, there are both tradeoffs and synergies which arise from a global environmental policy targeting excess nitrogen fertilizer use.

Groundwater Depletion

Freshwater availability is a planetary boundary that has begun to receive more attention from earth system scientists (Richardson et al. 2023). Water shortages are of critical significance to the global food system, as agriculture is the largest consumer of freshwater worldwide, accounting for roughly 70% of all freshwater withdrawals, of which more than half is ‘consumed’ in the form of evaporation and transpiration (Wisser et al. 2010). Groundwater withdrawals are a growing share of total freshwater usage. Wada et al. (2014) estimate that global groundwater depletion tripled over the fifty years from 1960-2010 and project that it will double again by the end of this century, resulting in 40% of human water consumption being supplied by from nonsustainable resources by 2100 (Wada and Bierkens 2014). This has led to dire predictions about global food security as groundwater supplies are exhausted (Famiglietti 2014).

In a recent paper Haqiqi, Perry, and Hertel (2022) explore the connection between groundwater, irrigation, agricultural production and food security using a gridded economic modeling framework (SIMPLE-G). Specifically, the authors assess the impacts of a global groundwater policy that restricts excessive groundwater withdrawals to their estimated rate of average annual recharge. This policy has spillover effects into land use, as those areas currently exceeding planetary boundaries, via excessive withdrawals, account for more than 12% of global crop production. If there were no further adjustments, and all of the crop production relying on unsustainable groundwater withdrawals were lost, Famiglietti's (2014) prediction of "skyrocketing food prices and profound economic and political ramifications" would indeed make sense. Assuming a global price elasticity of demand for food of 0.33, and therefore a price flexibility of 3, this would result in a permanent 36% rise in global food prices, with much larger increases in the most affected locations. This would indeed have a disastrous impact on food security.

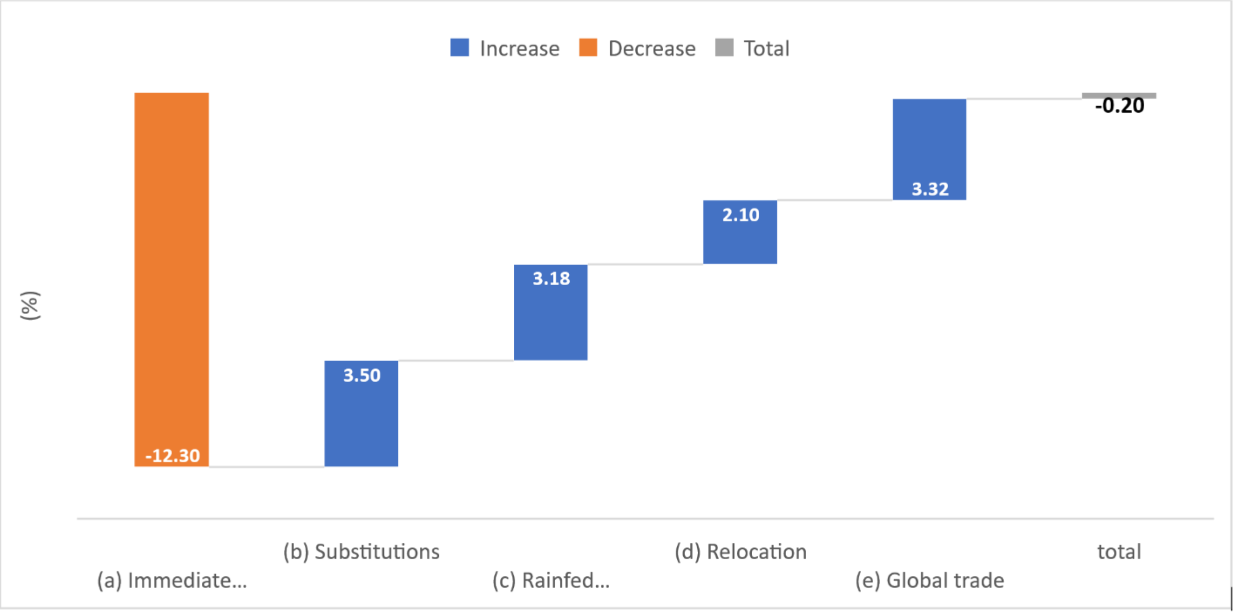


Figure 8. Response of global crop output to global groundwater sustainability restrictions. Entry (a) is the impact absent economic adaptations. Margins of adaptation include: (b) on-farm substitutions of other inputs for groundwater, (c) reversion to rainfed production, (d) relocation within the country and (e) international trade. The final entry shows the impact of the sustainability policy on global crop output after economic adaptations have taken place. Source: Haqiqi, Perry and Hertel (2022).

However, when prices rise, there are a variety of market-mediated responses, starting with substitution of surface water for groundwater, where this is feasible (Figure 8). Deficit irrigation (reducing the frequency and/or amount of irrigation water applied) as well as investments in improved irrigation equipment to make better use of scarce water are additional on-farm adaptations. Taken together, Haqiqi, Perry, and Hertel (2022) estimate that these on-farm measures could offset about one-quarter of the production loss (3.5%) at the global level (Figure 8, first blue bar). A second avenue for adaptation is to stop irrigating altogether, and allow the irrigated cropland to revert to rainfed production. The authors estimate that this would recoup another one-quarter of the total production loss (3.18%). A further adaption involves relocating production within the country. In response to higher prices, locations that are not currently cultivated could be converted to cropland, thereby offsetting another 2.1% of the global production loss. Finally, there is the option for some countries to simply import more of their food, displacing production to more resource-abundant countries. Haqiqi, Perry, and Hertel (2022) estimate that this increase in 'virtual water trade' could additionally offset more than 3% of the global production loss. In the end, they argue that the decline in global crop output would be less than one percent of total production ('total' grey bar in Figure 8). Of course, the authors point out, some of these adaptations will have a deleterious impact on other planetary boundaries as a consequence of cropland expansion into natural areas as well as increasing intensification of production in response to higher crop prices and these must also be considered in a comprehensive analysis.

While the long run impact of groundwater restrictions on global agricultural markets is unlikely to be as dramatic as anticipated by the physical scientists, these market-mediated responses can be devastating to local communities. Indeed, in many locations, vibrant agricultural economies have grown up around these groundwater-driven farming systems. What will happen to them if such sustainability policies are put in place? Haqiqi et al. (2022) identify local communities where agricultural employment might fall by as much as 50% in the face of these global groundwater restrictions. What are the implications of such dramatic shocks to the local economy? Ray et al. (2023) explore this question for the more limited case of groundwater restrictions in the Western US. They highlight the importance of labor market rigidities in governing the effectiveness and equity impacts of such conservation policies. In the US, there is recent evidence that farm labor is becoming less mobile (Fan et al. 2015). Ray et al. (2023) show that, as labor becomes less mobile, conservation policies tend to become less effective, even as these same policies have more dramatic impacts on local wages. Therefore, we cannot accurately assess the consequences of efforts to respect planetary boundaries without considering the potential (or lack thereof) for local adaptation and the consequences for household wellbeing.

Summary and Conclusions: Six Lessons from Economic Analysis of Planetary Boundaries

What lessons can be drawn from this literature and the associated attempts to bring economic analysis to bear on attempts to restore planetary boundaries associated with the food system?

Most research on planetary boundaries ignores economics and is policy agnostic: In a thoughtful review of the evolution of research on planetary boundaries, Bierman and Kim (2020) highlight the 'boundaries of planetary boundaries'. They note the apolitical, earth system science-driven nature of the original planetary boundaries formulation led by Johan Rockström (2009). Those authors did not attempt to include policy makers and other stakeholders in these early discussions. Yet, as we have seen from the examples explored above, the economic policies required to protect these planetary boundaries can have dramatic impacts on local communities as well as entire countries. Furthermore, once one moves into the realm of economic policies, tradeoffs and synergies emerge that are often ignored by the earth system scientists who simply wish to make the food system 'fit' into these planetary boundaries. Where rigid boundaries are prescribed, Barbier and Burgess (2019) demonstrate that, in the absence of appropriate pricing and investment in natural capital, these policies may actually speed up the demise of the remaining safe operating space. In short, there is great scope for economists to engage with, and make constructive contributions to, the community of scholars studying planetary boundaries.

Market-mediated spillovers are pervasive and give rise to tradeoffs across planetary boundaries: In failing to model the explicit policy interventions required to respect the planetary boundaries, earth system scientists typically overlook the way in which markets will respond to the desired interventions. For example, Gerten et al. (2020) demonstrate that 'feeding ten billion people is possible within four terrestrial planetary boundaries' by reallocating agricultural production, water and nitrogen use, while also reducing food loss and altering diets. However, this biophysical feasibility assessment does not address how these changes will be attained in a world of hundreds of millions of independent farmers. When Haqiqi et al. (2024) embed these same biophysical relationships into an economic model focusing on the planetary boundaries associated with nitrate pollution, they find that a nitrate leaching tax will have significant market-mediated spillover effects. These include: the relocation of production, both within and across countries as well as the reallocation of nitrogen fertilizer from targeted to other areas of agricultural production. Absent complementary policies, these market-mediated spillovers can exacerbate pollution elsewhere, as well as inducing cropland expansion into environmentally sensitive areas.

Synergies arise when conservation aimed at one planetary boundary reduces the intensity of production, thereby benefitting other planetary boundaries: Intensive agriculture often places stress on multiple planetary boundaries. Nowhere is this more pronounced than in Northern India, where Green Revolution technologies, relying on intensive irrigation and fertilization of crops, coupled with government subsidies for groundwater pumping, have led to serious depletion of groundwater as well as water quality and health challenges (Brainerd and Menon 2014; Dangar, Asoka, and Mishra 2021). As shown by Haqiqi et al. (2024), policies focusing on reductions in nitrate leaching offer a dual benefit of reducing groundwater extraction through the relocation of production to areas where production is less fertilizer intensive.

Market adaptations generally moderate the impact of planetary boundary conservation measures on food prices: A legitimate concern with enforcing planetary boundaries related to the food system is the resulting impact on food prices and hence exacerbating food insecurity. The specter of food shortages arising from excessive groundwater depletion offers a case in point (Famiglietti 2014; Wada, Van Beek, and Bierkens 2012). However, Liu et al. (2014) demonstrate that international trade can play a significant role in moderating the impacts of future water scarcity on food security. Similar findings are obtained in the context of scenarios where groundwater depletion is curtailed to remain within planetary boundaries (recall Figure 8 above). The same economic mechanisms come into play when restrictions on nitrogen fertilizer applications are applied (Haqiqi et al. 2024). In short, by ignoring economic adaptations, physical scientists tend to overstate the impact on food prices of localized interventions focused on conservation measures related to land and water use.

The impact of planetary boundary policies on local communities can be dramatic, and the community responses will shape the effectiveness and equity impacts of these policies: While economic adaptations can moderate the food price impacts of policies aimed at respecting planetary boundaries, they are likely to exacerbate the consequences for local communities. Consider parts of California's Central Valley, where local farming systems can rely heavily on unsustainable extraction of groundwater. In some cases, enforcement of a sustainability standard will require termination of groundwater pumping with dramatic consequences for local employment. Ray et al. (2023) estimate that wages in some parts of the Central Valley could fall by as much as 25%. Those authors show that the mobility of workers across sectors as well as across labor markets will determine not only the incidence of such a groundwater sustainability policy, but also the effectiveness of the policy itself in determining the stated goal. In short, we cannot ignore community responses in assessing the likely impacts of attempts to enforce planetary boundaries. This requires analysis far beyond the realm of the earth system scientists defining these environmental limits. In an attempt to address these issues of equity, the field of 'Donut Economics' has emerged (Raworth 2017). Here, the idea is to treat the planetary boundaries as the outer layer of the donut, with the inner layer relating to the social foundation for a 'regenerative and distributive economy'. In response to these concerns, Rockström and colleagues have revised their concept of planetary boundaries – to focus on 'safe and just earth system boundaries' in which social justice considerations further constrain these boundaries (Rockström et al. 2023).

Global-Local-Global analysis is essential for tackling planetary boundary challenges and identifying solutions: The strong temptation for many researchers studying planetary boundaries – particularly those related to land and water use – is to undertake location-specific studies. Indeed, as the agricultural economics profession is well aware, most sustainability issues are inherently local, with impacts and solutions depending on weather, soils, topography, technology and community governance. However, the global food system is fundamentally demand-driven. Farmers grow crops in order to satisfy consumer demand, and, as the growth in global food system trade and investment will attest, potential consumers reside across the entire globe. In order to understand the drivers behind contemporary food system sustainability challenges, a global approach is required. Indeed, in a study of future groundwater stress in the Western US, Haqiqi et al. (2023) conclude that the most important drivers of unsustainable withdrawals in that region arise from population and income growth outside the United States. Local decision makers need access to estimates of these global change drivers in order to formulate effective policies. And these local decisions will likely have spillover effects, as noted above (Figure 6). Hence the need for global-to-local-to-global analysis of sustainability policies (Hertel et al. 2023). This will require a synthesis of research focused on global economic analysis with studies undertaking geospatial analysis at the subnational level (Hertel et al. 2019). Furthermore, this research will have to be undertaken in close collaboration with earth system scientists as well as other disciplines. Stimulating such collaborations in the context of global-to-local-to-global analysis is the goal of the NSF-funded GLASSNET project (https://glassnet.net). Readers are invited to join this network of networks and participate in the associated workshops, early career scholar exchanges and training courses.

References

Alston, J.M., J.S. James, M.A. Andersen, and P.G. Pardey. 2010. *Persistence Pays: U.S. Agricultural Productivity Growth and the Benefits from Public R&D Spending*. Natural Resource Management and Policy 34. Springer New York. http://link.springer.com/chapter/10.1007/978-1-4419-0658-8_8.

Avetisyan, Misak, Alla Golub, Thomas Hertel, Steven Rose, and Benjamin Henderson. 2011. “Why a Global Carbon Policy Could Have a Dramatic Impact on the Pattern of the Worldwide Livestock Production.” *Applied Economic Perspectives and Policy* 33 (4): 584–605. https://doi.org/10.1093/aepp/ppr026.

Baldos, U. L. C., Alfredo Cisneros-Pineda, K.O. Fuglie, and T. W. Hertel. 2024. “Adoption of Modern Crop Varieties Limited Biodiversity Losses and Terrestrial Carbon Emissions in the Tropics.” *In Review*.

Barbier, Edward B., and Joanne C. Burgess. 2019. “Scarcity and Safe Operating Spaces: The Example of Natural Forests.” *Environmental and Resource Economics* 74 (3): 1077–99. https://doi.org/10.1007/s10640-019-00360-9.

———. 2024. “Economics of Peatlands Conservation, Restoration and Sustainable Management.” *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4695533.

Biermann, Frank, and Rakhyun E. Kim. 2020. “The Boundaries of the Planetary Boundary Framework: A Critical Appraisal of Approaches to Define a ‘Safe Operating Space’ for Humanity.” *Annual Review of Environment and Resources* 45 (1): 497–521. https://doi.org/10.1146/annurev-environ-012320-080337.

Brainerd, Elizabeth, and Nidhiya Menon. 2014. “Seasonal Effects of Water Quality: The Hidden Costs of the Green Revolution to Infant and Child Health in India.” *Journal of Development Economics* 107 (March):49–64. https://doi.org/10.1016/j.jdeveco.2013.11.004.

Bureau, Jean Christophe, and Jesús Antón. 2022. “Agricultural Total Factor Productivity and the Environment: A Guide to Emerging Best Practices in Measurement.” Paris: OECD. https://doi.org/10.1787/6fe2f9e0-en.

Busch, Jonah, and Kalifi Ferretti-Gallon. 2017. “What Drives Deforestation and What Stops It? A Meta-Analysis.” *Review of Environmental Economics and Policy* 11 (1): 3–23. https://doi.org/10.1093/reep/rew013.

Ceballos, Gerardo, Paul R. Ehrlich, Anthony D. Barnosky, Andrés García, Robert M. Pringle, and Todd M. Palmer. 2015. “Accelerated Modern Human–Induced Species Losses: Entering the Sixth Mass Extinction.” *Science Advances* 1 (5): e1400253. https://doi.org/10.1126/sciadv.1400253.

Chambers, Robert G. 2016. “Thinking About Agricultural Productivity Accounting in the Presence of By-Products.” White Paper No. 16–02. Department of Agricultural and Resource Economics, Univ, Maryland.

Chaudhary, Abhishek, and Thomas Kastner. 2016. “Land Use Biodiversity Impacts Embodied in International Food Trade.” *Global Environmental Change* 38 (May):195–204. https://doi.org/10.1016/j.gloenvcha.2016.03.013.

Christianson, Laura, John Tyndall, and Matthew Helmers. 2013. “Financial Comparison of Seven Nitrate Reduction Strategies for Midwestern Agricultural Drainage.” *Water*

Resources and Economics 2–3 (October):30–56. https://doi.org/10.1016/j.wre.2013.09.001.

Cisneros-Pineda, Alfredo, Abhishek Chaudhary, U. L. C Baldos, Yolanda Sung, and T. W Hertel. 2024. “Evolving Demographic Trends Will Shape Planetary Biodiversity.” *In Review*.

Coomes, Oliver T., Bradford L. Barham, Graham K. MacDonald, Navin Ramankutty, and Jean-Paul Chavas. 2019. “Leveraging Total Factor Productivity Growth for Sustainable and Resilient Farming.” *Nature Sustainability* 2 (1): 22–28. https://doi.org/10.1038/s41893-018-0200-3.

Crippa, M., E. Solazzo, D. Guizzardi, F. Monforti-Ferrario, F. N. Tubiello, and A. Leip. 2021. “Food Systems Are Responsible for a Third of Global Anthropogenic GHG Emissions.” *Nature Food* 2 (3): 198–209. https://doi.org/10.1038/s43016-021-00225-9.

Dangar, Swarup, Akarsh Asoka, and Vimal Mishra. 2021. “Causes and Implications of Groundwater Depletion in India: A Review.” *Journal of Hydrology* 596 (May):126103. https://doi.org/10.1016/j.jhydrol.2021.126103.

Dinerstein, E., C. Vynne, E. Sala, A. R. Joshi, S. Fernando, T. E. Lovejoy, J. Mayorga, et al. 2019. “A Global Deal For Nature: Guiding Principles, Milestones, and Targets.” *Science Advances* 5 (4): eaaw2869. https://doi.org/10.1126/sciadv.aaw2869.

Ehui, Simeon K., and Dunstan S. C. Spencer. 1993. “Measuring the Sustainability and Economic Viability of Tropical Farming Systems: A Model from Sub-Saharan Africa.” *Agricultural Economics* 9 (4): 279–96. https://doi.org/10.1016/0169-5150(93)90018-8.

Ewert, Frank, Roland Baatz, and Robert Finger. 2023. “Agroecology for a Sustainable Agriculture and Food System: From Local Solutions to Large-Scale Adoption.” *Annual Review of Resource Economics* 15 (Volume 15, 2023): 351–81. https://doi.org/10.1146/annurev-resource-102422-090105.

Exposito-Alonso, Moises, Tom R. Booker, Lucas Czech, Lauren Gillespie, Shannon Hateley, Christopher C. Kyriazis, Patricia L. M. Lang, et al. 2022. “Genetic Diversity Loss in the Anthropocene.” *Science* 377 (6613): 1431–35. https://doi.org/10.1126/science.abn5642.

Famiglietti, J. S. 2014. “The Global Groundwater Crisis.” *Nature Climate Change* 4 (11): 945–48. https://doi.org/10.1038/nclimate2425.

Fan, Maoyong, Susan Gabbard, Anita Alves Pena, and Jeffrey M. Perloff. 2015. “Why Do Fewer Agricultural Workers Migrate Now?” *American Journal of Agricultural Economics* 97 (3): 665–79. https://doi.org/10.1093/ajae/aau115.

FAO, UN. 2023. “The State of Food and Agriculture.” https://doi.org/10.4060/cc7724en.

Fuglie, Keith O., and Ruben G. Echeverria. 2024. “The Economic Impact of CGIAR-Related Crop Technologies on Agricultural Productivity in Developing Countries, 1961–2020.” *World Development* 176 (April):106523. https://doi.org/10.1016/j.worlddev.2023.106523.

Fuglie, Keith, Srabashi Ray, Uris Lantz C. Baldos, and Thomas W. Hertel. 2022. “The R&D Cost of Climate Mitigation in Agriculture.” *Applied Economic Perspectives and Policy* 44 (4): 1955–74. https://doi.org/10.1002/aepp.13245.

Fuglie, K.O., Timothy Benton, Yu Sheng, Julien Hardelin, Koen Mondelaers, and David Laborde. 2016. “Metrics of Sustainable Agricultural Productivity.” G-20 MACS White Paper.

Fuglie, K.O., T. W. Hertel, D. B. Lobell, and N. B. Villoria. 2024. “Agricultural Productivity and Climate Mitigation.” *Annual Review of Resource Economics* 16.

Galloway, James N., John D. Aber, Jan Willem Erisman, Sybil P. Seitzinger, Robert W. Howarth, Ellis B. Cowling, and B. Jack Cosby. 2003. “The Nitrogen Cascade.” *BioScience* 53 (4): 341–56. https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2.

Gautam, Madhur, David Laborde, Abdullah Mamun, Will Martin, Valeria Pineiro, and Rob Vos. 2022. *Repurposing Agricultural Policies and Support: Options to Transform Agriculture and Food Systems to Better Serve the Health of People, Economies, and the Planet*. World Bank. https://doi.org/10.1596/36875.

Gerten, Dieter, Vera Heck, Jonas Jägermeyr, Benjamin Leon Bodirsky, Ingo Fetzer, Mika Jalava, Matti Kummu, et al. 2020. “Feeding Ten Billion People Is Possible within Four Terrestrial Planetary Boundaries.” *Nature Sustainability* 3 (3): 200–208. https://doi.org/10.1038/s41893-019-0465-1.

Gliessman, Steve. 2015. “Agroecology: A Growing Field.” *Agroecology and Sustainable Food Systems* 39 (1): 1–2. https://doi.org/10.1080/21683565.2014.965869.

Golub, A., T.W. Hertel, H.L. Lee, S.K. Rose, and B. Sohngen. 2009. “The Opportunity Cost of Land Use and the Global Potential for Greenhouse Gas Mitigation in Agriculture and Forestry.” *Resource and Energy Economics* 31 (4): 299–319. https://doi.org/10.1016/j.reseneeco.2009.04.007.

Golub, Alla A., Benjamin B. Henderson, T.W. Hertel, Pierre J. Gerber, Steven K. Rose, and Brent Sohngen. 2012. “Global Climate Policy Impacts on Livestock, Land Use, Livelihoods, and Food Security.” *Proceedings of the National Academy of Sciences*, September, 1–6. https://doi.org/10.1073/pnas.1108772109.

Haqiqi, Iman, Laura Bowling, Sadia Jame, Uris Baldos, Jing Liu, and Thomas Hertel. 2023. “Global Drivers of Local Water Stresses and Global Responses to Local Water Policies in the United States.” *Environmental Research Letters* 18 (6): 065007. https://doi.org/10.1088/1748-9326/acd269.

Haqiqi, Iman, Jannes Breier, Christoph Mueller, Dieter Gerten, and Thomas W Hertel. 2024. “Market-Mediated Spillover Effects from Targeting a Single Planetary Boundary: Tradeoffs and Synergies.” *In Preparation*.

Haqiqi, Iman, Chris J. Perry, and Thomas W. Hertel. 2022. “When the Virtual Water Runs out: Local and Global Responses to Addressing Unsustainable Groundwater Consumption.” *Water International* 47 (7): 1060–84. https://doi.org/10.1080/02508060.2023.2131272.

Hasegawa, Tomoko, Shinichiro Fujimori, Petr Havlík, Hugo Valin, Benjamin Leon Bodirsky, Jonathan C. Doelman, Thomas Fellmann, et al. 2018. “Risk of Increased Food Insecurity under Stringent Global Climate Change Mitigation Policy.” *Nature Climate Change* 8 (8): 699–703. https://doi.org/10.1038/s41558-018-0230-x.

Havlík, Petr, Hugo Valin, Mykola Gusti, Erwin Schmid, David Leclère, Nicklas Forsell, Mario Herrero, et al. 2015. *Climate Change Impacts and Mitigation in the Developing World: An Integrated Assessment of the Agriculture and Forestry Sectors*. Policy Research Working Papers. The World Bank. https://doi.org/10.1596/1813-9450-7477.

Heisey, Paul W, and Keith O. Fuglie. 2018. “Agricultural Research Investment and Policy Reform in High-Income Countries.” ERR-249. Washington DC, USA: U.S. Department of Agriculture, Economic Research Service.

Henderson, B., A. Golub, D. Pambudi, T. Hertel, C. Godde, M. Herrero, O. Cacho, and P. Gerber. 2017. “The Power and Pain of Market-Based Carbon Policies: A Global Application to Greenhouse Gases from Ruminant Livestock Production.” *Mitigation and*

Adaptation Strategies for Global Change, January, 1–21. https://doi.org/10.1007/s11027-017-9737-0.

Hertel, Thomas. 2021. "Growing Food and Protecting Nature Don't Have to Conflict – Here's How They Can Work Together." The Conversation. March 9, 2021. http://theconversation.com/growing-food-and-protecting-nature-dont-have-to-conflict-heres-how-they-can-work-together-146069.

Hertel, Thomas W., Elena Irwin, Stephen Polasky, and Navin Ramankutty. 2023. "Focus on Global–Local–Global Analysis of Sustainability." *Environmental Research Letters* 18 (10): 100201. https://doi.org/10.1088/1748-9326/acf8da.

Hertel, Thomas W, Navin Ramankutty, and U.L.C. 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 (38): 13799–804.

Hertel, Thomas W., Thales A. P. West, Jan Börner, and Nelson B. Villoria. 2019. "A Review of Global-Local-Global Linkages in Economic Land-Use/Cover Change Models." *Environmental Research Letters* 14 (5): 053003. https://doi.org/10.1088/1748-9326/ab0d33.

Humpenöder, Florian, Kristine Karstens, Hermann Lotze-Campen, Jens Leifeld, Lorenzo Menichetti, Alexandra Barthelmes, and Alexander Popp. 2020. "Peatland Protection and Restoration Are Key for Climate Change Mitigation." *Environmental Research Letters* 15 (10): 104093. https://doi.org/10.1088/1748-9326/abae2a.

Hussein, Zekarias, T.W. Hertel, and Alla Golub. 2013. "Climate Change Mitigation Policies and Poverty in Developing Countries." *Environmental Research Letters* 8 (3): 035009. https://doi.org/10.1088/1748-9326/8/3/035009.

Iowa State University. 2013. *Iowa Nutrient Reduction Strategy*. Ames, IA: Iowa Department of Agriculture and Land Stewardship, Iowa Department of Natural Resources, and Iowa State University College of Agriculture and Life Sciences. https://www.nutrientstrategy.iastate.edu/.

IPBES Secretariat. 2019. "Global Assessment Report on Biodiversity and Ecosystem Services | IPBES Secretariat." May 17, 2019. https://www.ipbes.net/node/35274.

Jenkins, Clinton N., Stuart L. Pimm, and Lucas N. Joppa. 2013. "Global Patterns of Terrestrial Vertebrate Diversity and Conservation." *Proceedings of the National Academy of Sciences* 110 (28): E2602–10. https://doi.org/10.1073/pnas.1302251110.

Johnson, Justin Andrew, Uris Lantz Baldos, Erwin Corong, Thomas Hertel, Stephen Polasky, Raffaello Cervigni, Toby Roxburgh, Giovanni Ruta, Colette Salemi, and Sumil Thakrar. 2023. "Investing in Nature Can Improve Equity and Economic Returns." *Proceedings of the National Academy of Sciences* 120 (27): e2220401120. https://doi.org/10.1073/pnas.2220401120.

Leclère, David, Michael Obersteiner, Mike Barrett, Stuart H. M. Butchart, Abhishek Chaudhary, Adriana De Palma, Fabrice A. J. DeClerck, et al. 2020. "Bending the Curve of Terrestrial Biodiversity Needs an Integrated Strategy." *Nature* 585 (7826): 551–56. https://doi.org/10.1038/s41586-020-2705-y.

Lenzen, M., D. Moran, K. Kanemoto, B. Foran, L. Lobefaro, and A. Geschke. 2012. "International Trade Drives Biodiversity Threats in Developing Nations." *Nature* 486 (7401): 109–12. https://doi.org/10.1038/nature11145.

Liu, Jing, Laura C Bowling, Christopher J. Kucharik, Sadia A Jame, Uris Baldos, Larissa Jarvis, Navin Ramankutty, and Thomas W Hertel. 2023. “Tackling Policy Leakage and Targeting Hotspots Could Be Key to Addressing the ‘Wicked’ Challenge of Nutrient Pollution from Corn Production in the U.S.” *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/acf727.

Liu, Jing, T.W. Hertel, F. Taheripour, Tingju Zhu, and C. Ringler. 2014. “International Trade Buffers the Impact of Future Irrigation Shortfalls.” *Global Environmental Change* 29 (November):22–31. https://doi.org/10.1016/j.gloenvcha.2014.07.010.

Martin, Will, and Rob Vos. 2024. “Options for Reducing Greenhouse Gas Emissions from Agriculture and Food Systems.” In . Ravello, Italy.

McCarl, B.A., and U.A. Schneider. 2001. “Climate Change: Greenhouse Gas Mitigation in U.S. Agriculture and Forestry.” *Science* 294 (5551): 2481–82. https://doi.org/10.1126/science.1064193.

Mehrabi, Zia, Erle C. Ellis, and Navin Ramankutty. 2018. “The Challenge of Feeding the World While Conserving Half the Planet.” *Nature Sustainability* 1 (8): 409–12. https://doi.org/10.1038/s41893-018-0119-8.

Murray, B., B. Sohngen, A. Sommer, B. Depro, K. Jones, B.A. McCarl, D. Gillig, B. de Angelo, and K. Andrasko. 2005. “Greenhouse Gas Mitigation Potential in US Forestry and Agriculture.” EPA Report 430-R-05-006.

Otto, Friederike E.L. 2017. “Attribution of Weather and Climate Events.” *Annual Review of Environment and Resources* 42 (1): 627–46. https://doi.org/10.1146/annurev-environ-102016-060847.

Raworth, Kate. 2017. *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*. White River Junction, Vermont: Chelsea Green Publishing.

Ray, Srabashi, Iman Haqiqi, Alexandra E. Hill, J. Edward Taylor, and Thomas W. Hertel. 2023. “Labor Markets: A Critical Link between Global-Local Shocks and Their Impact on Agriculture.” *Environmental Research Letters* 18 (3): 035007. https://doi.org/10.1088/1748-9326/acb1c9.

Richardson, Katherine, Will Steffen, Wolfgang Lucht, Jørgen Bendtsen, Sarah E. Cornell, Jonathan F. Donges, Markus Drüke, et al. 2023. “Earth beyond Six of Nine Planetary Boundaries.” *Science Advances* 9 (37): eadh2458. https://doi.org/10.1126/sciadv.adh2458.

Rockström, Johan, Joyeeta Gupta, Dahe Qin, Steven J. Lade, Jesse F. Abrams, Lauren S. Andersen, David I. Armstrong McKay, et al. 2023. “Safe and Just Earth System Boundaries.” *Nature* 619 (7968): 102–11. https://doi.org/10.1038/s41586-023-06083-8.

Rockström, Johan, Will Steffen, Kevin Noone, Åsa Persson, F. Stuart Chapin, Eric F. Lambin, Timothy M. Lenton, et al. 2009. “A Safe Operating Space for Humanity.” *Nature* 461 (7263): 472–75. https://doi.org/10.1038/461472a.

Schulte-Uebbing, L. F., A. H. W. Beusen, A. F. Bouwman, and W. de Vries. 2022. “From Planetary to Regional Boundaries for Agricultural Nitrogen Pollution.” *Nature* 610 (7932): 507–12. https://doi.org/10.1038/s41586-022-05158-2.

secretariat. 2019. “Global Assessment Report on Biodiversity and Ecosystem Services | IPBES Secretariat.” May 17, 2019. https://www.ipbes.net/node/35274.

Seppelt, Ralf, Channing Arndt, Michael Beckmann, Emily A. Martin, and Thomas W. Hertel. 2020. “Deciphering the Biodiversity–Production Mutualism in the Global Food Security Debate.” *Trends in Ecology & Evolution* 0 (0). https://doi.org/10.1016/j.tree.2020.06.012.

Smerald, Andrew, David Kraus, Jaber Rahimi, Kathrin Fuchs, Ralf Kiese, Klaus Butterbach-Bahl, and Clemens Scheer. 2023. "A Redistribution of Nitrogen Fertiliser across Global Croplands Can Help Achieve Food Security within Environmental Boundaries." *Communications Earth & Environment* 4 (1): 1–11. https://doi.org/10.1038/s43247-023-00970-8.

Stevenson, J., D. Byerlee, Nelson Villoria, T. Kelley, and M. Maredia. 2012. "Agricultural Technology, Global Land Use 488 and Deforestation: A Review." *Proc Natl Acad Sci US* In review.

Ürge-Vorsatz, Diana, Sergio Tirado-Herrero, Navroz Dubash, and Franck Lecocq. 2014. "Measuring the Co-Benefits of Climate Change Mitigation." *Annual Review of Environment and Resources* 39 (October):549–82. https://doi.org/10.1146/annurev-environ-031312-125456.

US Department of Commerce, NOAA. n.d. "Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases." Accessed June 20, 2024. https://gml.noaa.gov/ccgg/trends/.

U.S. Interagency Working Group. 2021. "Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide." Technical Report. Washington D.C.

Valin, Hugo, Thomas Hertel, Benjamin Leon Bodirsky, Tomoko Hasegawa, and Elke Stehfest. 2021. "Achieving Zero Hunger by 2030 A Review of Quantitative Assessments of Synergies and Tradeoffs amongst the UN Sustainable Development Goals." Report. Center for Development Research (ZEF) in cooperation with the Scientific Group for the UN Food System Summit 2021. https://doi.org/10.48565/scgr2021-2337.

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 (12): 125002. https://doi.org/10.1088/1748-9326/ab4f57.

Vitousek, Peter M., John D. Aber, Robert W. Howarth, Gene E. Likens, Pamela A. Matson, David W. Schindler, William H. Schlesinger, and David G. Tilman. 1997. "Human Alteration of the Global Nitrogen Cycle: Sources and Consequences." *Ecological Applications* 7 (3): 737–50. https://doi.org/10.1890/1051-0761(1997)007[0737:HAOTGN]2.0.CO;2.

Wada, Y., D. Wisser, and M. F. P. Bierkens. 2014. "Global Modeling of Withdrawal, Allocation and Consumptive Use of Surface Water and Groundwater Resources." *Earth System Dynamics* 5 (1): 15–40. https://doi.org/10.5194/esd-5-15-2014.

Wada, Yoshihide, and Marc F. P. Bierkens. 2014. "Sustainability of Global Water Use: Past Reconstruction and Future Projections." *Environmental Research Letters* 9 (10): 104003. https://doi.org/10.1088/1748-9326/9/10/104003.

Wada, Yoshihide, L. P. H. Van Beek, and Marc F. P. Bierkens. 2012. "Nonsustainable Groundwater Sustaining Irrigation: A Global Assessment." *Water Resources Research* 48 (6): 2011WR010562. https://doi.org/10.1029/2011WR010562.

Wezel, A., M. Casagrande, F. Celette, J. F. Vian, A. Ferrer, and J. Peigné. 2014. "Agroecological Practices for Sustainable Agriculture. A Review." *Agronomy for Sustainable Development* 34 (1): 1–20.

Wisser, D., B. M. Fekete, C. J. Vörösmarty, and A. H. Schumann. 2010. "Reconstructing 20th Century Global Hydrography: A Contribution to the Global Terrestrial Network-Hydrology (GTN-H)." *Hydrol. Earth Syst. Sci.* 14 (1): 1–24. https://doi.org/10.5194/hess-14-1-2010.

Wuepper, David, Ilsabe Wiebecke, Lara Meier, Sarah Vogelsanger, Selina Bramato, Andrea Fürholz, and Robert Finger. 2024. “Agri-Environmental Policies from 1960 to 2022.” *Nature Food* 5 (4): 323–31. https://doi.org/10.1038/s43016-024-00945-8.

Yu, Zicheng, Julie Loisel, Daniel P. Brosseau, David W. Beilman, and Stephanie J. Hunt. 2010. “Global Peatland Dynamics since the Last Glacial Maximum.” *Geophysical Research Letters* 37 (13). https://doi.org/10.1029/2010GL043584.

Zuidema, Shan, Jing Liu, Maksym G. Chepeliev, David R. Johnson, Uris Lantz C. Baldos, Steve Frolking, Christopher J. Kucharik, Wilfred M. Wollheim, and Thomas W. Hertel. 2023. “US Climate Policy Yields Water Quality Cobenefits in the Mississippi Basin and Gulf of Mexico.” *Proceedings of the National Academy of Sciences* 120 (43): e2302087120. https://doi.org/10.1073/pnas.2302087120.

Zuidema, Shan, Wilfred M Wollheim, Christopher J Kucharik, and Richard B Lammers. 2024. “Existing Wetland Conservation Programs Miss Nutrient Reduction Targets.” *PNAS Nexus* 3 (4): pgae129. https://doi.org/10.1093/pnasnexus/pgae129.