April 25, 2013

Global Change and the Challenges of Sustainably Feeding a Growing Planet[1]

Thomas W. Hertel[2]

Purdue University

[1] White Paper prepared for the MIT-CSIS Energy Sustainability Challenge Forum, May 6-7, 2013: Washington, D.C. The author acknowledges valuable discussions with Uris Baldos, Derek Byerlee and David Lobell. He would also like to acknowledge support for the underlying research into the climate-food-energy-land-water nexus from US DOE, Office of Science, Office of Biological and Environmental Research, Integrated Assessment Research Program, Grant No. DE-SC005171, and from the National Science Foundation, grant 0951576: DMUU: Center for Robust Decision Making on Climate and Energy Policy.

[2] The author is Distinguished Professor of Agricultural Economics and Executive Director of the Center for Global Trade Analysis. Address correspondence to: Hertel@purdue.edu .

Setting the stage [3]

Since the 2007/2008 commodity crisis, there has been a resurgence of interest in the sustainability of the world's food system and its contributions to feeding the world's population as well as to ensuring the environmental sustainability of the planet. The elements of this 'grand challenge' are by now quite familiar. The number of people which the world must feed is expected to increase by another 2 billion by 2050 (Bloom 2011). When coupled with significant nutritional improvements for the 2.1 billion people currently living on less than $2/day (World Bank 2008, p.1), this translates into a very substantial rise in the demand for agricultural production. FAO estimates the increased demand at 70 percent of current production, with a figure nearer 100% in the developing countries (Bruinsma 2009, p.2).

Over the past century, global agriculture has managed to offer a growing population an improved diet, primarily by increasing productivity on existing cropland. However, a number of authors have documented signs of slowing yield growth for key staple crops (Byerlee and Deininger 2010, Box 2.1). And public opposition to genetically modified crops has slowed growth in the application of promising biotechnology developments to food production in some parts of the world. At the same time, the growing use of biomass for energy generation has introduced an important new source of industrial demand in agricultural markets (Energy Information Agency 2010). To compound matters, water, a key input into agricultural production, is rapidly diminishing in availability in many parts of the world (McKinsey & Co 2009), and many soils are degrading (Lepers et al. 2005).

In addition, agriculture and forestry are increasingly envisioned as key sectors for climate change mitigation policy. When combined, farming and land use change – much of it induced by

[3] This section draws heavily on my AAEA Presidential Address (T. Hertel 2011).

agriculture - currently account for about one-third of global greenhouse gas emissions (Baumert, Herzog, and Pershing 2009), but, if incorporated into a global climate policy, these sectors could contribute up to half of all mitigation in the near term, at modest carbon prices (A. Golub et al. 2009). Any serious attempt to curtail these emissions will involve changes in the way farming is conducted, as well as placing limits on the expansion of farming – particularly in the tropics, where most of the agricultural land conversion has come at the expense of forests, either directly (Holly K Gibbs et al. forthcoming) or indirectly via a cascading of land use requirements with crops moving into pasture and pasture into forest (Barona et al. 2010). Limiting the conversion of forests to agricultural lands is also critical to preserving the planet's biodiversity (Green et al. 2005). These factors will restrict the potential for agricultural expansion in the wake of growing global demands.

Finally, agriculture and forestry are likely to be the economic sectors whose productivity is most sharply affected by climate change (D. B. Lobell, Schlenker, and Costa-Roberts 2011; Schlenker and Roberts 2009). This will shift the pattern of global comparative advantage in agriculture (J. Reilly et al. 2007) and may well reduce the productivity of farming in precisely those regions of the world where poverty and malnutrition are most prevalent (T. Hertel, Burke, and Lobell 2010), while increasing yield variability and the vulnerability of the world's poor (Ahmed, Diffenbaugh, and Hertel 2009).

Set in this way, the world's stage offers a rather bleak picture when it comes to ensuring the long run sustainability of the planet. However, as with most such predictions, the issues are rather more complex than portrayed in 'headline' reports. The goal of this background paper is to delve into greater detail on the determinants of long run sustainability in the global system of food production and the land, water and energy resources upon which it relies, and which the food system shapes. In most of the analysis, I focus on the target year 2050. My logic (apart from joining the bandwagon of other studies with this focal point) is that I believe this to be the period during which the challenge to sustainable agricultural production will be greatest. There are reasons for this conclusion. Firstly, sometime around mid-century we expect global population growth to level off. Based on income projections, this is also the point at which we can expect most of the world's population to have upgraded their dietary requirements, thereby limiting further growth in food demand arising from increases in income. From a climate mitigation policy point of view, 2050 is also quite interesting, as the coming decades are the period over which land-based mitigation policies are likely to play the most important role – particularly those aimed at sequestering a portion of the massive increases in CO2 emissions projected over the near term. And finally, from a more practical perspective, 2050 is at the outer limit of (indeed probably beyond) the ability of economists to project patterns of long term economic growth.

With the stage thus set, let me turn to some key points which will shape global sustainability outcome between the present day and 2050.

Population and income will remain key drivers of global change, but their relative importance will change

Population and income are the twin drivers of global change which attract the most attention – and deservedly so. If the world's population does nothing to change its behavior, but demographics result in a doubling of the number of mouths to feed, clothe, house, transport and entertain, the planetary burden would effectively double. While a global population of 14-15 billion people is at the upper limit of demographic projections for the end of this century (Roberts 2011), even the projected 2050 population increase of an additional 2 billion people appears daunting in the context of a world which is already straining the environment and natural resource base. The question of population size notwithstanding, as we look forward to 2050, it is really the increase in per capita income that is of greatest concern. Just consider the following thought experiment. Which scenario is likely to generate the greatest stress on the world's resources: (a) Adding an additional 2 billion people consuming at average per capita global consumption levels, or (b) the prospect of today's 7 billion people consuming at the same rate as the current US population? Viewed from a carbon emissions point of view, the answer is very clear. Keeping per capita consumption at current levels, which boosting population by 30% would generate about a 30% rise in carbon emissions. However, raising consumption levels of current population to those of the United States has been estimated to result in a four-fold rise in global carbon emissions (Huber 2013).

Economists have sought to explain these differences in consumption behavior across countries using prices and income as well as other variables (Dowrick and Quiggin 1994), and these statistical studies can then be used to project how future consumption patterns are likely to change in the future.[4] Baldos and Hertel (Baldos and Hertel 2013b) draw on the statistical work of Muhammed et al. (2011) in order to formally compare the relative role of population and income as drivers of global food demand and land use changes over two alternative 45 year times spans: 1961-2006 and 2006-2050. From the point of view of global crop output growth, they find that population growth was roughly twice as important as growth in per capita income over the

[4] One might reasonably ask: How can we know how consumers in Ethiopia will behave when they become as rich as consumers in South Africa? Will Chinese consumers follow the path charted by consumers in Taiwan? In order to predict the evolution of consumer spending as incomes rise, economists look at behavior across many countries, seeking to identify broad patterns across wide ranges of income. There is considerable evidence that consumers follow a common pattern with regard to broad-based consumption behavior (e.g., food, housing etc.) (Dowrick and Quiggin 1994). Muhammed et al. estimate the response of food consumption to changing prices and income. They find some relationships that are important for projections purposes – namely the diminishing marginal impact of income on consumption, as well as the fact that consumers' responsiveness to food price changes also diminishes as incomes rise. Hertel and Baldos use these relationships to "backcast" global food demand, prices and land use, and find that, at global scale, they are able to reproduce historical food consumption over a 45 year period. This gives us some hope that we can say something useful about the next 45 years.

historical period. However, in the projections period, the role of population growth in boosting crop output and prices is only about one-third as large as in the historical period, and it is now dominated by the role of growing per capita income as one looks ahead to 2050. This is a very significant change in the international landscape, with important implications for the growth in global food demand.

Much of the increased crop output demanded over the period to 2050 will be in the form of feedstuffs for livestock. This is because the demand for animal protein grows strongly as consumers move out of absolute poverty and seek to enrich their diets. Livestock can be produced via extensive production techniques (e.g., grazing in the case of ruminant livestock, or foraging in the case of poultry and pigs) or intensive techniques, epitomized by the ‘factory farms’ in which thousands of animals are fed concentrated feed rations in confined facilities (F. Taheripour, Hurt, and Tyner 2013). These two types of technologies have dramatically different implications for the food system and for environmental quality. The issue is somewhat akin to the discussion of ‘land-sparing’ vs. ‘land-caring’ technologies in crop production (Green et al. 2005), which poses the question: Is it better for society to undertake intensive production techniques which may have locally harmful environmental consequences, but which spare resources at global scale, or is it preferable to use the world’s resources more extensively, spreading the environmental impact of agricultural production more thinly across the globe?

Over the last 20 years, there has been a shift, worldwide, towards more intensive livestock production techniques, with marked implications for the composition of agricultural land use (F. Taheripour, Hurt, and Tyner 2013). Globally, area devoted to permanent meadows and pastures – typical of extensive livestock production -- fell by about 70 million hectares over the first decade of this century, with animal feed crops such as hay and fodder falling as well.

Meanwhile, the area devoted to corn and oilseeds – key inputs into concentrated livestock diets -- has risen by about 60 million hectares over the same period (F. Taheripour, Hurt, and Tyner 2013). Much of this increase has been destined for livestock – either directly through feed concentrate, or indirectly as by-products of biofuel production (dried distillers grains or oilseed meal). This increase in area has been especially notable in South America. Indeed Brazil has become a key supplier of soybeans to the Chinese livestock industry, where rising incomes have translated into strong growth in consumer demand for animal products. In short, rising incomes will continue to be an important driver of global demand for agricultural land, eclipsing population in relative importance as the growth rate in the latter continues to slow.

Energy Prices are the Wildcard Driver behind Global Land Use Change

While it is widely understood that energy prices play an important role in shaping energy-related exploration, supply, innovation and consumption, it is less-well appreciated how important energy prices can be in shaping global land use – particularly in the current era of close linkages between the energy and agricultural markets driven by growing biofuel production (Tyner 2010). Indeed, the global expansion in corn and oilseeds area over the past decade is in part due to the growth in biofuels (Farzad Taheripour and Tyner 2013). Looking forward there is great uncertainty in this linkage between energy and agricultural markets, and this uncertainty is largely fueled by the tremendous uncertainty in energy prices facing the world economy.

Steinbuks and Hertel (Steinbuks and Hertel 2013) explore the relationship between energy prices and global land use over the course of the 21st century. Their framework allows a role for energy prices to influence fertilizer prices, thereby altering the incentive to intensify agricultural production. They also allow for the substitution of first and second-generation biofuels for petroleum products in liquid fuels. In considering possible trajectories for oil prices over the 21st century, they take as their low-price case a scenario in which oil prices remain flat at current levels throughout the century. This is the ‘fracking’ scenario in which new technologies for extracting fossil fuels, as well as new fossil fuel discoveries, result in ample supplies. For the high oil price scenario, the authors extrapolate to 2100 the growth rates embedded in the baseline US Energy Information Agency scenario. As a result, real oil prices grow at an average annual rate of 3%/year, reaching a peak of $700/bbl by 2100. The authors find that, in the context of a model of optimal global land use (designed to mimic behavior of forward-looking investors), the flat energy price scenario results in much less agricultural land conversion by 2100, relative to the EIA baseline scenario. Indeed, by 2100, global land use for food and biofuels is 400 million hectares lower than under the baseline. Half of this difference is accounted for by reduced area devoted to food production – cheap energy results in cheap fertilizer and higher yields -- and half is due to the elimination of bioenergy crops in the context of this low oil prices scenario. This highlights the sensitivity of global land use to long run energy prices. Whether or not we live in a cheap energy future will have great influence over the pattern of global land conversion for food and biofuels.

Water will become more prominent in our discussion of global sustainability

It is impossible to speak about sustainability of the global food system today without considering the role of water. Agriculture accounts for 70% of freshwater withdrawals globally, and irrigated lands contribute to 42% of global crop production (Bruinsma 2009). And in some regions these withdrawals are in excess of what is sustainable over the long run. Bruinsma projects that, by 2050, 13 countries will be devoting more than 40% of their renewable water resources to irrigation – a level considered to indicate very high stress. In South Asia, he estimates that this figure will rise from 36% to 39%. Of course, as with any resource that is under-priced, or even free in many cases, there are tremendous opportunities for efficiency gains and these likely hold the key to future sustainability of water use in agriculture.

In a more comprehensive global study, undertaken at the level of individual river basins, and utilizing a suite of economic and hydrological models, Rosegrant et al. (2013) compare Irrigation Water Supply Reliability (IWSR) indices across two 2050 scenarios. The first is the Business As Usual (BAU) scenario under which agricultural productivity and water use efficiency in the agricultural, industrial and domestic uses sectors reflect current trends. In contrast, under the Bioeconomy (BIO) scenario, they allow for faster agricultural productivity growth, due to increased R&D expenditures, as well as significant improvements in water use efficiency – particularly for the non-agricultural sectors. This, too, is important for irrigation, since water available for agriculture is often a residual, based on availability other water demands have been satisfied. The authors find that, under their BAU scenario, the global IWSR – the ratio of irrigation water supplies to demand (1.0 is best) falls from 0.77 in 2000 to 0.62 in 2050. The decline is particularly sharp in the East and South Asia regions, as well as Central Asia. In contrast, under the BIO scenario, higher agricultural productivity and increased water use efficiency allow for a global IWSR of 0.73 in 2050, with far smaller declines in the Asian regions, as well as increases in some of the other regions. In short, more making more efficient use of water – both in irrigation and in non-farm uses – is critical for ensuring global sustainability of agricultural production in 2050.

Future food prices will depend critically on technological progress in agriculture

Pinning down technological progress is the key to understanding the long run trajectory of the agricultural sector, food prices and global land use. A good place to start is with a careful examination of the historical record. Given the widespread availability of data on global agriculture over the past 50 years, one would think that there might be a consensus about the historical evolution of technological progress in this sector and the prospects for future growth. However, this is not the case. Indeed, there have emerged two broad camps on this issue. For lack of better terminology, and for the sake of sharpening their differences, I will label them: the pessimists and the optimists, although many of the individuals writing in this area offer a more balanced perspective in their own writings.

To paraphrase their arguments, the pessimists suggest that science has largely ‘worked its magic’ and potential crop yields (i.e., the maximum attainable under ideal conditions) are reaching a biophysical plateau beyond which the ability of plants to convert sunlight, water and nutrients into grain cannot be easily increased. Fischer et al. (2013) discuss the biophysical components of growth in potential yields, noting that potential yields depend on the product of three key factors: the photo-synthetically active radiation intercepted by the green crop tissue, the radiation use efficiency of the plant, and the harvest index -- which measures the portion of the plant devoted to grain. They note that the first and the third elements of this formula are constrained by firm biophysical limits and therefore constrain further potential yield growth to roughly 20% beyond current levels (Fischer, Byerlee, and Edmeades 2013). They see scope for improving the radiation use efficiency of plants, but suggest this is an area of great uncertainty. In short, *increasing the potential crop yields is a challenging task.*

Of course, the likelihood of increasing potential yields depends critically on investment in basic research and development activities. This is yet another source of fuel for the pessimists. Alston, Beddow and Pardey (2009) document a slowdown in the rate of increase in US public agricultural R&D spending from nearly 4%/year in the two decades from 1950-1970 to about

1%/year over the 1990-2007 period. They argue that this slowdown, which was mirrored in Japan and Europe, has translated into slower productivity growth in these more recent decades. The potential for boosting yields with this dwindling pool of R&D funds is further challenged by the reluctance of large portions of the world to embrace GMOs, which have been shown to enable more rapid yield growth in the case of maize (Fischer, Byerlee, and Edmeades 2013).[5] In light of the very long lag time between initial research investments and the ultimate impact on production (Alston, Pardey, and Ruttan 2008), this is a sources of serious concern.

While the pessimists acknowledge that yields could be increased by closing the gap between potential yields and actual yields, which is quite large in many parts of the world, they can legitimately argue that this gap is there for a reason (Neumann et al. 2010) – poor infrastructure, limited information, lack of credit, etc. and these barriers will not be eliminated overnight. And boosting both potential and actual yields throughout much of the tropics will be made more difficult in the face of climate change and rising temperatures, coupled with more erratic rainfall (more on this below). Add to this the emerging water scarcity noted in the previous section and you have the formula to a slowdown in yield growth.[6] The bottom line for the pessimists is that the world faces a rate of yield growth which will be insufficient to meet the growing demands of the world's growing, increasingly wealthy population. This means that prices will rise, thereby affecting the food security of the poor. Since higher prices will increase

[5] These authors compare maize yield growth in Iowa with that in France and Italy. In the 25 years prior to the introduction of GM corn (the mid-1990's), yields in the two regions grew at very similar rates. However, since 1996, GM-based maize yields in Iowa have grown at about 2%/year, whereas they have remained largely flat in France and Italy. Of course, there were other factors at work during this period, include reform of the EU Common Agricultural Policy which reduced the incentives for farmers to intensify production.
[6] Yet another, more pedestrian argument behind the slowdown in yield growth is simple arithmetic. Since trend yields tend to grow at a linear rate (e.g., 1 bushel of grain/acre/year), as the yield level grows, this annual increment represents a smaller and smaller % of the total, thereby resulting in a slowing *rate* of growth (Cassman, Grassini, and Wart 2010).

rates of cropland conversion, thereby boosting GHG emissions, the coming 50 years look rather bleak through the pessimists' lens.

The optimists take largely the same historical information and come to a rather different conclusion. They predict that productivity growth will be adequate to meet demand growth. Indeed, some would argue that agricultural prices are likely to resume their long run downward trend once the current supply-demand imbalance -- stemming from the combination of bad weather and biofuels -- is resolved. As with the pessimists, there are varied elements to the optimists' case. Firstly, they point out that, even though yield growth is slowing, so too is population growth. Therefore, in the footrace between supply and demand, yields no longer need to grow at their historical rates in order to keep pace with demand growth. Rather than the growing at 2.2%/year as was the case over the 1961-2007 period, the FAO estimates that crop production will only need to grow at half that rate – or 1.1%/year over the 2007-2050 period (Bruinsma 2009).

The optimists also appeal to the same yield gap estimates identified by the pessimists in order to suggest that, given sufficient economic incentives, as well as improved infrastructure, massive increases in output can be achieved by closing these gaps between potential yields and yields actually achieved at the farm level. For example, Licker et al. (2010) estimate that global maize production could be increased by 50% by closing the gap between current farmer yields in low income countries and those in the advanced economies producing under identical biophysical conditions (i.e. similar climate and soils). Of course, if these yield gaps were easy to close, then profit-minded farmers would surely have done so already. The point is simply that, from a biophysical point of view, there is great potential for boosting yields based on currently deployed technologies.

There is a deeper source of disagreement between some members of the two camps, and this relates to the measurement of productivity growth and the source of the recent slowdown in yields. While many attribute the yield slowdown to an approaching ‘biophysical limit’, others suggest that the slowing productivity growth has been driven by economic factors. In his global scale analysis of historical changes in agricultural output, Fuglie (2012) decomposes the sources of global output growth, by decade, for the period: 1961-2009. He isolates four distinct factors: area expansion, irrigation, intensification (more non-land inputs such as fertilizer for each hectare of land) and total factor productivity (TFP) growth. While global output growth over this period was fairly steady, ranging between 2 – 2.5%%/year, the sources of output growth have varied greatly.

In this decomposition of historical output growth, Fuglie attributes the bulk of the record output growth in the 1960’s (recall the green revolution) to the *intensification of production*. This source of growth remained high in the 1970’s, but dwindled over subsequent decades, until, in the 1990’s, intensification accounted for only about 10% of total output growth. He attributes this decline in the rate of growth in non-land input use to the steady decline in crop prices over this period. On the other hand, TFP, which is a function of historical investments in R&D, was the factor which kept global agricultural output growth above 2% throughout the 1990’s. In the most recent decade (2001-2009), Fuglie estimates that TFP growth remained at its record high growth rate, but the price sensitive contributors to output growth – intensification and land area – picked up in response to the price rises over this period. As a result, he finds that total output growth averaged 2.5%/year over this period – a rate not seen since the 1960’s. This recent TFP performance leads Fuglie to be quite optimistic about the future. He points to the long lag time in R&D, suggesting some persistence in the current rates of TFP growth. When coupled with the considerable upside potential for further intensification and area expansion in response to record high prices, this leads him to conclude that future output growth will be strong. Baldos and Hertel (2013b) incorporate Fuglie's TFP projections into the SIMPLE model of global agriculture and land use and find that the resulting 2050 crop prices are considerably below current levels – a result which bolsters the optimists' position.

I will leave the last word on this topic to Fischer, Byerlee and Edmeades (2013), who have studied in depth the issue of agricultural productivity growth and the potential ensuring food security in 2050. Their book offers a comprehensive, interdisciplinary perspective, invoking a mix of local case studies, regional scale, and global analyses. In their closing chapter, they offer the kind of balanced assessment that one might expect of a seasoned team of authors:

> In conclusion we do not foresee calamity as do some, nor are we lulled into complacency, especially by the advocates of biotechnology. But we do see multidisciplinary agricultural science as a key to success. Together with complementary investments in infrastructure and institutions, and relative peace, the world should manage. It won't be ideal, there will be environmental costs, but the perfect should not be allowed to get in the way of what is scientifically feasible, pragmatic and broadly acceptable socially in agriculture.

Climate Change will alter the path of productivity, affecting land use, nutrition and poverty

One of the largest sources of uncertainty in future productivity projections for agriculture is climate change. Assessing the impact of climate change on agriculture is a daunting task which can be broken down into four basic steps (Alexandratos (2010, pp. 14-15)): (1) develop projections of future GHG concentrations based on long run projections of the global economy, (2) use the General Circulation Models (GCMs) developed by climate scientists to translate these GHG outcomes into spatially disaggregated deviations of temperature and precipitation from baseline levels, (3) superimpose these deviations on biophysical models to determine how they will affect plant growth and the productivity of agriculture in different agro-ecological conditions, and finally (4) perturb models of the agricultural economy to determine changes in production, consumption, trade, etc. And, in the case of a fully integrated assessment model such as MIT's linked modeling system (John Reilly et al. 2012), the results from step (4) feedback to (1). Each of these steps entails considerable uncertainty, and that uncertainty is compounded as one follows the chain down from global economic projections to climate impacts. Adaptation strategies, including changing planting dates and the development and introduction of new varieties, further complicate the last two steps. In short, this activity is not for the faint of heart! In light of the fact that this white paper is being paired with a companion paper by some of the world's leading scientists working on this issue, I will focus my comments in this section on items (3) and (4): How will the changing climate affect the trajectory of global agricultural productivity discussed in the previous section? And how will this altered trajectory influence crop prices, land use, nutrition and poverty?

At the outset, there are two key points to be made. Firstly, there is already evidence that climate trends – in particular, higher temperatures -- are affecting crop yields (D. B. Lobell, Schlenker, and Costa-Roberts 2011). The global impacts of these historical changes are most pronounced for maize and wheat, and less so for soybeans and rice. Secondly, in the medium term -- in this case 2050 – effects of trend increases in temperature on crop yields are likely to be modest – translating roughly into a yield loss of 1.5%/decade – or about one year of trend productivity growth for each 10 years (David B. Lobell and Gourdji 2012). And these are expected to be roughly offset by the benefits of heightened atmospheric CO2 concentrations.

Broadly similar results are emerging from the biophysical crop modeling community. This work is being summarized in a series of forthcoming papers growing out of the AgMIP Agricultural Crop Modeling Inter-comparison Project. This work seeks to characterize the degree of uncertainty in climate impacts by simulating a wide range of globally gridded crop models in the context of a single climate change scenario (Rosenzweig et al. 2013). In order to sharpen their findings, and identify sources of differences across models, they focus on the most extreme warming scenario being considered presently, namely the Representative Concentration Pathway 8.5 scenario. In this work, they find broad agreement for maize and wheat across the crop models regarding the sign of the climate impacts, which show high-latitude yield increases, relative to baseline and low-latitude decreases. In the case of soybeans, the results are more varied, with relatively minor or positive impacts in most regions (Rosenzweig et al. 2013). An important finding of this crop model inter-comparison is that the dominant source of difference across models is their treatment of the CO2 fertilization effect, which is the main source of the gains in crop yield in the temperate regions under this extreme climate change scenario. This raises an important point about the nature of the uncertainty in climate impacts over this century. These impacts are the net result of potentially large, but uncertain, negative yield effects due to higher temperatures, and also potentially large, but highly uncertain, positive effects of non-CO2 fertilization on crops. This results in massive uncertainty about the ultimate impacts on climate change on global agriculture, food prices and land use. The net effects in 2050 could be positive (i.e., increased global output) or negative. In their overall assessment of the net effects of climate change on yields, Lobell and Gourdji (2012) suggest that the impacts could be as large at a quarter of overall yields trends. This would have a strong impact on production, prices and global land use.

While significant resources are being devoted to the further development of the crop models in order to narrow the range of uncertainty, they remain prisoners of their history which, in many cases, was focused on facilitation of crop management decisions, as opposed to the investigation of climate extremes. Indeed, developers of crop models have long cautioned against their use in climate change studies, given the lack of development and testing in extreme climate conditions (J. W. White, Hoogenboom, and Hunt 2005; Jeffrey W. White et al. 2011). For example, a recent review of 221 studies using crop models for climate change impacts, which spanned over 70 different models, found that only six studies considered the effects of elevated CO_2 on canopy temperature, and similarly few studies considered direct heat effects on seed set or leaf senescence (Jeffrey W. White et al. 2011). Overall, of the five key processes by which climate change affects crop yields, David Lobell (personal communication) estimates that most crop models capture only about two-and-a-half. He notes that most models include treatment of crop development and photosynthesis responses to temperature, but omit heat effects on grain set and damage from pests and invasive species. And, in general these omitted processes are thought to become more damaging with climate change, so models may provide estimates biased toward positive values. For example, invasive species are omitted from most analyses of the impact of climate change on crop production. Yet these species are generally better suited for adaptation to changing environmental conditions due to rapid evolution, broad tolerance to environmental shocks and strong seed dispersal (Ziska and Dukes 2011). This suggests that climate change will favor development of these plants, at the expense of commercial crops, thereby generating additional costs and/or crop losses under climate change. It is also important to note that the types of processes omitted by models tend to be more important in tropical than in temperate systems, suggesting that the existing estimates of low-latitude crop losses from climate change are likely to understate the true effects (Hertel and Lobell, 2012).

A critically important piece of the puzzle posed by climate impacts on global sustainability is the potential for farmers to adapt to the changing climate (J. M. Reilly et al. 2002). Yet many of the studies of climate impacts on agriculture limit the types of adaptation considered to biophysical variables like planting and harvesting dates and crop mix. Some studies allow for the development of new varieties which are better attuned to the new climatic conditions (T. Hertel and Lobell 2012). However, with potentially large impacts on regional yields and global prices (G. Nelson et al. 2009), the scope for adaptation is likely much greater than is captured in many of the biophysical models of climate change. Of course, much of this adaptation will depend on investments in agricultural R&D, access to credit by producers seeking to make adaptive investments (e.g., irrigation), information and access to markets which might permit producers to specialize in crops which are better suited to their new environment. Hertel and Lobell (2012) argue that, in many cases, these adaptation opportunities will be most limited in the developing countries. Add to this, the fact that tropical agriculture is likely to be harder hit by climate change (Rosenzweig et al. 2013), and is likely to have less biophysical room to adapt due to higher starting temperatures and moisture-constrained growing seasons (Deryng et al. 2011) and climate change begins to look more like a regional distributional issue, as opposed to a global food security question.

Baldos and Hertel (2013a)examine the impact in 2050 of projected changes in temperature and precipitation using the global yield estimates of Mueller et al. (2010). Their analysis focuses on the consumption channel through the resulting rise in food prices (regional per capita incomes are held constant at their baseline levels). They find that climate change (ignoring the CO_2 fertilization effects) boosts malnutrition globally by about 50 million people in 2050, relative to projections without climate change. They also compute the change in malnutrition gap, which widens by about 5 kcal/capita/day in low income countries as a consequence of the combined impacts of higher temperatures and altered precipitation on global crop yields.

Hertel, Burke and Lobell (2010) have explored the impact of climate change on incomes as well as consumption, calculating the resultant changes in poverty rates across a range of developing countries in the tropics. They explore a variety of scenarios for the year 2030, ranging from a ‘worst case’ scenario in which yield impacts are more severe than expected to a ‘best case’ one which the yield impacts are generally positive. An important finding in their study is that *agricultural producers in much of the developing world could benefit from adverse climate change* due to the ensuing rise in crop prices. Upon reflection, this is hardly surprising. Consider the case of the US drought/heat wave of 2012 during which average corn yields fell by about 25%, relative to trend. It is difficult to say precisely how much corn price responded to this shock, but Abbott et al. (2011) estimate the resulting corn price rise to have been about 50%. Therefore, for any producer who experienced the average yield loss, and who was able to take advantage of the higher prices (i.e. had not already sold their crop in the futures market), their revenues would have risen as a result of the drought. Of course, for those farmers in regions unaffected by the extreme weather (e.g., parts of Minnesota), the rise in corn prices was a huge windfall. The same phenomenon is present in the climate change scenario analyzed by Hertel et al. They find that, under the worst case scenario, regions expected to be relatively lightly affected (e.g., Chile) experience significant gains as a result of the climate scenario, while those producers in those regions most severely affected (Sub-Saharan Africa) are hurt. Of course, higher prices unambiguously hurt the urban poor, who are net food buyers and who do not gain from potential increases in farm income. The authors conclude that the national poverty impact of adverse climate change depends on whether the country's yields are hit harder than average by climate change and whether the poverty is concentrated in the rural areas or in the urban ones.

Future Agricultural Land Use Faces Stiff Competition from Environmental Services

While the near-term impacts of climate change on crop production are likely to be modest – building to potentially more dramatic impacts after 2050, the same cannot be said of the impacts of policies aimed at mitigating climate change. Here, the largest consequences for land use are likely to come *before* the middle of this century. For evidence of the potential importance of these policies, one has only to look at two current examples: biofuels and REDD+ (reduced environmental degradation and deforestation) policies. While there were many factors which led to the introduction of renewable fuel standards relating to biofuels in the EU and the US, there is no doubt that the 'renewable' element was an important component. By utilizing fuels based on biological feedstocks which sequester carbon during their growth, advocates had high hopes for biofuels to become part of the climate solution. Indeed, as recently as 2007, the consensus of the scientific community was that corn ethanol, in particular, could contribute significantly to GHG abatement (Farrell et al. 2006). As the US ramped up its ethanol capacity in response to the RFS, a massive amount of corn was removed from the food system. Indeed, half of the increase in global cereals consumption during the 2005/6 – 2007/8 period was due to US ethanol production Westhoff (2010, pp. 14-15). The consequences for patterns of production and land use world-wide have been the subject of intensive research (Searchinger et al. 29; Thomas W. Hertel et al. 2010; Al-Riffai, Dimaranan, and Laborde 2010), and the global footprint of the US corn ethanol program and the EU biodiesel program can been seen in the pattern of land use change over this period (Farzad Taheripour and Tyner 2013).

Another area in which patterns of agricultural land use have been shaped by climate mitigation policies is that of REDD+. Evidence suggests that much of newly converted cropland in the tropics was in closed forest 20 years ago (H. K. Gibbs et al. 2010). REDD+ policies are designed to slow this conversion of land, which has been the source of a large share of global emissions over this period. One of the most significant efforts has been undertaken in the Philippines, with support from the Indonesian government (Busch et al. 2013). It is estimated that the resulting moratorium on conversion of forests to oil palm plantations, had it been in place from 2000-2010, would have reduced Indonesia's emissions from deforestation by 578 $MtCO_2e$, or about 8% of that which actually occurred. So putting this moratorium in place is an important environmental accomplishment. However, there has been considerable opposition from local interests groups and it has also curtailed production of a commodity for which there is rapidly growing demand in Asia – particularly by low income households. There are many other REDD+ projects currently underway, each of which will contribute to reducing GHG emissions, and each of which will potentially contribute to shifting backwards the supply of land for agriculture. The net effect is unambiguous – higher food prices – it is only the magnitude of the ensuing price increase which remains in question.

Reilly et al. (2012) explore a variety of climate policy futures and the ensuing consequences for land use and food prices. In the case where they allow for perfect pricing of carbon from land use, in addition to pricing carbon from energy combustion. (In this scenario, biofuels as a mitigation strategy expand strongly in the second half of this century.) The authors estimate that such a climate policy would result in dramatic food price increases – nearly doubling relative to their no policy baseline. Golub et al. (2012) have simulated the impact of a global forest carbon sequestration policy on land use and food prices within the current economic environment. They find that this environmental policy has a particularly strong impact on agricultural land use in the tropical, non-Annex I countries. Indeed, they find that this land use effect is strong enough to largely eliminate the leakage which results when agricultural GHG mitigation is only undertaken in the Annex I region. Overall, land values rise significantly, as do food prices. Hussein et al. (2013) delve more deeply into the distributional impacts of a global forest carbon sequestration policy. They conclude that, since most of the benefits of this policy flow to landowners, and the poor control relatively little land, the predominant impact of forest carbon sequestration on the poor would be through higher food prices – something which leads to poverty increases in the majority of their sample countries.

However, climate mitigation policies are not the only source of future competition for land. As households become wealthier, economists predict that they will demand more environmental services, including natural parks and biodiversity (Jacobsen and Hanley 2009; Kauppi et al. 2006; Antoine, Gurgel, and Reilly 2008). Steinbuks and Hertel (2012) incorporate the demand for ecosystem services into their long run model of global land use and estimate that the optimal amount of area set aside for natural uses could triple over the course of the 21st century.

In summary, there will be growing competition for scarce, productive land, over the coming century. Increased emphasis on GHG mitigation, biodiversity and other ecosystem services will only sharpen this competition, resulting in higher land prices and higher food costs than would otherwise be observed.

Globalization offers both opportunities and threats to sustainability

Globalization is playing an important role in the changing pattern of global land use. As markets become more integrated, agricultural production is shifting towards those regions that are relatively land abundant (e.g., South America) and away from those regions that are land scarce (e.g., East Asia) (A. G. Golub and Hertel 2008). This frees up agricultural land in the land scarce regions for other uses. This process of “land-sorting” is something that has been observed over the last century by geographers (Lambin and Meyfroidt 2011), and it occurs not only at the international level, but also within countries (Mather and Needle 1998). By allocating land to those uses for which it is best-suited, humanity is able to boost the overall basket of goods and services obtained from this finite resource.

However, where property rights are ill-defined, there is also a down-side to globalization which is most evident in cases where carbon-rich, bio-diverse tropical forests are subject to open-access. By offering producers the chance to sell large amounts of commercial products at nearly fixed world price, integration into the world market can provide strong incentives for producers to expand production into ecologically sensitive regions (Angelsen and Kaimowitz 2001). This is further exacerbated in cases where deforestation and farming are viewed as a means of asserting property rights over communal lands (Lambin and Meyfroidt 2011). Meyfroidt et al. (2010) identify the spillover effects which arise through international trade when countries seeking to set aside forest lands end up importing forest products and encouraging deforestation elsewhere. Of course, avoided deforestation in one region may still result in reduced land cover change globally, depending on the relative productivity of the regions in question and the price responsiveness of global demand (T. Hertel 2012). One point that surfaces clearly in this discussion is that globalization greatly complicates the analysis of land use issues as heightens the necessity for global scale assessments of policies.

Implications for future research

This overview of some of the main findings from the literature on global sustainability, as it bears on the world's food system, highlights two points in particular. First of all, research published over the past decade has significantly advanced the knowledge frontier. We now understand that large biofuel programs in one part of the world have important ripple effects throughout the global economy, thereby affecting land use and associated GHG emissions. Researchers have identified critical temperature thresholds, above which significant yield losses will occur for the world's main grains and oilseed crops and related these extreme events to market volatility. The great potential for land-based mitigation policies to contribute to slowing the rate of GHG accumulation has been identified and the broad consequences for global land use and food prices have been characterized. And we now know much more about the potential for 'leakage' of environmental damage to other regions when one country sets aside forest lands or undertakes serious GHG abatement policies. Furthermore, these findings have been effectively communicated by researchers to the media and to the broader policy community.

This significant progress notwithstanding, there remains much to be done if we hope to be able to anticipate the impacts of major policy initiatives in the area of food, energy, water and land. Certainly further refinement of the mechanisms discussed previously in this paper remains a high priority. And there are many research programs currently targeting these issues. However, the most interesting research questions at this stage seem to be arising at geographic, disciplinary and policy *intersections*. Work at the intersections between disciplines, such as the collaboration between agronomists, hydrologists, climate scientists, ecologists and economists continues to be critical to assessing climate impacts on agriculture and the environment. The human impacts of such climate change require linking these changes to nutritional outcomes (G. C. Nelson et al. 2010) as well as small-holder households and poverty (T. Hertel, Burke, and Lobell 2010; Claessens et al. 2012). This work is still at a rudimentary stage.

There are also important interactions across resources. This is illustrated by a recent study exploring the land-water-energy-food nexus shows that factoring in water availability constraints to irrigation expansion sharply changes the pattern of global land use and GHG emissions in the wake of bioenergy development (Farzad Taheripour, Hertel, and Liu 2013). Another type of interaction is that between policies aimed at adaptation to climate change and those focusing on mitigation. Lobell et al. (2013) show that investment in research and development aimed at facilitating agricultural adaptation to higher temperatures can yield significant mitigation benefits. Indeed, they find that the adaptation research could be justified entirely on the grounds of the ensuring mitigation benefits.

One of the most important types of interactions in the context of global food and environmental sustainability is the interaction between local and global scales of analysis. On the one hand, the forces driving land use, environment and food security issues are global in nature, including population, income growth, biofuels, trade, etc. On the other hand, the impacts and policy responses (or lack thereof) are often highly localized. They depend on things like land tenure, soil and forest carbon stocks, species diversity, local climate and poverty rates. To understand these local scale impacts of the forces driving global change, one needs frameworks which facilitate communication across scales. Some excellent work is already underway in this area (John Reilly et al. 2012) and will be highlighted in the companion white paper. However, this is only a start. Many more groups need to be engaged in this type of work.

Perhaps the most severe constraint faced by those seeking to undertake global-local-global scale research on land use, food and environmental security is the absence of high quality, interoperable, readily accessible, time series data bases on global land cover, land use and tenure, irrigation and poverty (Hertel et al. 2010). With the ongoing revolution in satellite imagery, geospatial data and associated software, developing such data base infrastructure is well within our reach. However, the challenge has been to facilitate collaboration to ensure interoperability of these diverse data bases, facilitate regular updates, and tie these developments into the needs of decision makers. One successful example of such collaboration on global data bases (albeit focusing just at the global-national scales) is offered by the Global Trade Analysis Project (www.gtap.org). Recently we have proposed a similar activity in the geospatial arena: www.geoshareproject.org (T. W. Hertel and Villoria 2012). There is great potential for such global public goods to elevate the level of research and policy debate in this arena.

References

Abbott, Philip, Chris Hurt, and Wallace E. Tyner. 2011. "What's Driving Food Prices in 2011?" Issue Report. Farm Foundation.

Ahmed, Syud A, Noah S Diffenbaugh, and Thomas W Hertel. 2009. "Climate Volatility Deepens Poverty Vulnerability in Developing Countries." *Environmental Research Letters* 4 (3) (July): 034004. doi:10.1088/1748-9326/4/3/034004.

Alexandratos, Nikos. 2010. "Critical Evaluation of Selected Projections." In Rome, Italy.

Alston, Julian M., Jason M. Beddow, and Philip G. Pardey. 2009. "Agricultural Research, Productivity, and Food Prices in the Long Run." *Science* 325 (5945) (September 4): 1209–1210. doi:10.1126/science.1170451.

Alston, Julian M., Philip G. Pardey, and Vernon W. Ruttan. 2008. "Research Lags Revisited: Concepts and Evidence from U.S. Agriculture". Staff Paper 50091. University of Minnesota, Department of Applied Economics. http://ideas.repec.org/p/ags/umaesp/50091.html.

Angelsen, A., and D. Kaimowitz, ed. 2001. *Agricultural Technologies and Tropical Deforestation*. Vol. Agricultural technologies and tropical deforestation. CAB International.

Antoine, C., A. Gurgel, and J. Reilly. 2008. "Will Recreation Demand for Land Limit Biofuels Production?" *Journal of Agricultural & Food Industrial Organization* 6 (2): 1–27.

Baldos, U.L., and T. W Hertel. 2013a. "Global Food Security in 2050: The Role of Agricultural Productivity and Climate Change." *Australian Journal of Agricltural and Resource Economics* in review.

Baldos, U.L., and T. W. Hertel. 2013b. "Understanding the Drivers Behind Long Run Food Price Trends: Looking Back to See the Future." In Washington, D. C.

Barona, Elizabeth, Navin Ramankutty, Glenn Hyman, and Oliver T Coomes. 2010. "The Role of Pasture and Soybean in Deforestation of the Brazilian Amazon." *Environmental Research Letters* 5 (2) (April): 024002. doi:10.1088/1748-9326/5/2/024002.

Baumert, Kevin A., Timothy Herzog, and Jonathan Pershing. 2009. "Navigating the Numbers: Greenhouse Gas Data and International Climate Policy". Washington, DC, USA: World Resources Institute.

Bloom, David E. 2011. "7 Billion and Counting." *Science* 333 (6042) (July 29): 562 –569. doi:10.1126/science.1209290.

Bruinsma, Jelle. 2009. "The Resource Outlook to 2050. By How Much Do Land, Water Use and Crop Yields Need to Increase by 2050?" In *Session 2: The Resource Base to 2050: Will There Be Enough Land, Water and Genetic Potential to Meet Future Food and Biofuel Demands?* Rome, Italy.

Busch, J., R. N. Lubowski, E. Ashkenazi, K. Austin, A. Baccinni, F. Boltz, M. Farid, et al. 2013. "Reducing Emissions from Deforestation in Indonesia: Carbon Payments or a Moratorium on Concessions?" *In Preparation*.

Cassman, Kenneth G., Patricio Grassini, and Justin van Wart. 2010. "Crop Yield Potential, Yield Trends, and Global Food Security in a Changing Climate." In *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation*, edited by Daniel Hillel and Cynthia Rosenzweig, 1:37–51. ICP Series on Climate Change Impacts, Adaptation, and Mitigation. NJ, USA: World Scientific Publishing Co. Pte. Ltd.

Claessens, L., J.M. Antle, J. Stoorvogel, Validvia, R.O., Thornton, P.K., and Herrero, M. 2012. "A Method for Evaluating Climate Change Adaptation Strategies for Small-scale Farmers Using Survey, Experimental and Modeled Data." *Agricultural Systems* Forthcoming.

Deininger, Klaus W, and Derek Byerlee. 2010. *Rising Global Interest in Farmland: Can It Yield Sustainable and Equitable Benefits?* Washington, D. C.: The World Bank.

Deryng, D., W. J. Sacks, C. C. Barford, and N. Ramankutty. 2011. "Simulating the Effects of Climate and Agricultural Management Practices on Global Crop Yield." *Global Biogeochemical Cycles* 25 (May 20): 18 PP. doi:201110.1029/2009GB003765.

Dowrick, Steve, and John Quiggin. 1994. "International Comparisons of Living Standards and Tastes: A Revealed-Preference Analysis." *American Economic Review* 84 (1): 332–41.

Energy Information Agency. 2010. "Annual Energy Outlook 2010". Annual Energy Outlook DOE/EIA-0383(2010). Washington, DC, USA: US Department of Energy.

Farrell, Alexander E., Richard J. Plevin, Brian T. Turner, Andrew D. Jones, Michael O'Hare, and Daniel M. Kammen. 2006. "Ethanol Can Contribute to Energy and Environmental Goals." *Science* 311 (5760) (January 27): 506–508. doi:10.1126/science.1121416.

Fischer, R.A., D. Byerlee, and G. Edmeades. 2013. *Crop Yield and Food Security: Can Yield Increases Continue to Feed the World?* Canberra: ACIAR.

Fuglie, K. O. 2012. "Productivity Growth and Technology Capital in the Global Agricultural Economy." In *Productivity Growth In Agriculture: An International Perspective*, edited by Keith O. Fuglie, Sun Ling Wang, and V Eldon Ball, 335–368. Cambridge, MA, USA: CAB International.

Gibbs, H. K., A. S. Ruesch, F. Achard, M. K. Clayton, P. Holmgren, N. Ramankutty, and J. A. Foley. 2010. "Tropical Forests Were the Primary Sources of New Agricultural Land in the 1980s and 1990s." *Proceedings of the National Academy of Sciences* 107 (38) (August 31): 16732–16737. doi:10.1073/pnas.0910275107.

Gibbs, Holly K, A. S. Ruesch, F. Achard, M. Clayton, P. Holmgren, and N. Ramankutty. forthcoming. "Pathways of Agricultural Expansion Across the Tropics: Implications for Forest Conservation and Carbon Emissions." *Proceedings of the National Academy of Sciences*

Golub, Alla G, and Thomas W. Hertel. 2008. "Global Economic Integration and Land Use Change" 23 (3). Journal of Economic Integration: 463–488.

Golub, Alla, Benjamin B. Henderson, Thomas Hertel, Pierre Gerber, Steven Rose, and Brent Sohngen. 2012. "Global Climate Policy Impacts on Livestock, Land Use, Livelihoods and Food Security." *Proceedings of the National Academy of Sciences* In press.

Golub, Alla, Thomas Hertel, Huey-Lin Lee, Steven Rose, and Brent 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. doi:10.1016/j.reseneeco.2009.04.007.

Green, Rhys E., Stephen J. Cornell, Jorn P. W. Scharlemann, and Andrew Balmford. 2005. "Farming and the Fate of Wild Nature." *Science* 307 (5709) (January 28): 550–555. doi:10.1126/science.1106049.

Hertel, T. W, W. Britz, N. S Diffenbaugh, N. Ramankutty, and N. Villoria. 2010. "A Global, SpatiallyExplicit, OpenSource Data Base for Analysis of Agriculture, Forestry, and the Environment: Proposal and Institutional Considerations". Report to the UK Science Advisor. Department of Agricultural Economics, Purdue University. http://www.agecon.purdue.edu/foresight/proposal_spatial_database10-15-2010.pdf.

Hertel, T. W., and N.B. Villoria. 2012. “GEOSHARE: Geospatial Open Source Hosting of Agriculture, Resource & Environmental Data for Discovery and Decision Maki”. Purdue Global Policy Research Institute. http://www.purdue.edu/research/gpri/publications/documents/GEOSHAREwhitepaper-04-16-2012.pdf.

Hertel, Thomas. 2011. “The Global Supply and Demand for Land in 2050: A Perfect Storm?” *American Journal of Agricultural Economics* 93 (1). AAEA Presidential Address.

———. 2012. “Implications of Agricultural Productivity for Global Cropland Use and GHG Emissions: Borlaug Vs. Jevons.” *GTAP Working Paper No. 69*. http://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=4020.

Hertel, Thomas, Marshall Burke, and David Lobell. 2010. “The Poverty Implications of Climate-Induced Crop Yield Changes by 2030”. Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University.

Hertel, Thomas, and David Lobell. 2012. “Agricultural Adaptation to Climate Change in Rich and Poor Countries: Current Modeling Practice and Potential for Empirical Contributions.” *GTAP Working Paper No. 72*. http://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=4030.

Hertel, Thomas W., Alla G Golub, Andrew Jones, Michael O’Hare, Richard Plevin, and Daniel Kammen. 2010. “Global Land Use and Greenhouse Gas Emissions Impacts of US Maize Ethanol: Estimating Market-Mediated Responses.” *BioScience* (March).

Huber, Matthew. 2013. “Modelling of Climate Change: Implications for Food, Water, and Energy Security” presented at the Presentation to the class on “Global Land Use in 2050: Implications for Food Securtiy and the Environment,” February 12, Purdue University.

Hussein, Zekarias, Thomas Hertel, and Alla Golub. 2013. “Poverty Impacts of Climate Mitigation Policy.” *Under Review with Environmental Research Letters*.

Jacobsen, Jette, and Nick Hanley. 2009. “Are There Income Effects on Global Willingness to Pay for Biodiversity Conservation?” *Environmental and Resource Economics* 43 (2) (June 1): 137–160. doi:10.1007/s10640-008-9226-8.

Kauppi, Pekka E., Jesse H. Ausubel, Jingyun Fang, Alexander S. Mather, Roger A. Sedjo, and Paul E. Waggoner. 2006. “Returning Forests Analyzed with the Forest Identity.” *Proceedings of the National Academy of Sciences* 103 (46) (November 14): 17574–17579. doi:10.1073/pnas.0608343103.

Lambin, Eric F., and Patrick Meyfroidt. 2011. “Global Land Use Change, Economic Globalization, and the Looming Land Scarcity.” *Proceedings of the National Academy of Sciences* 108 (9) (March 1): 3465 –3472. doi:10.1073/pnas.1100480108.

Lepers, Erika, Eric F. Lambin, Anthony C. Janetos, Ruth S. DeFries, Frédéric Achard, Navin Ramankutty, and Robert J. Scholes. 2005. “A Synthesis of Information on Rapid Land-cover Change for the Period 1981–2000.” *BioScience* 55 (2): 115–124. doi:doi: 10.1641/0006-3568(2005)055[0115:ASOIOR]2.0.CO;2.

Licker, Rachel, Matt Johnston, Carol Barford, Jonathan A. Foley, Christopher J. Kucharik, Chad Monfreda, and Navin Ramankutty. 2010. “Mind the Gap: How Do Climate and Agricultural Management Explain the ‘yield Gap’ of Croplands Around the World?”

Lobell, D. B, U.L. Baldos, and T. W. Hertel. 2013. “Climate Adaptation as Mitigation: The Case of Agricultural Investments.” *Environmental Research Letters* 8. doi:doi:10.1088/1748-9326/8/1/015012.

Lobell, D. B., W. Schlenker, and J. Costa-Roberts. 2011. "Climate Trends and Global Crop Production Since 1980." *Science* 333 (May 5): 616–620. doi:10.1126/science.1204531.

Lobell, David B., and Sharon M. Gourdji. 2012. "The Influence of Climate Change on Global Crop Productivity." *Plant Physiology* 160 (4) (December 1): 1686–1697. doi:10.1104/pp.112.208298.

Mather, A S, and C L Needle. 1998. "The Forest Transition: a Theoretical Basis." *Area* 30 (2): 117–124. doi:10.1111/j.1475-4762.1998.tb00055.x.

McKinsey & Co. 2009. *Charting Our Water Future: Economic Frameworks to Inform Decision-making*. 2030 Water Resources Group: McKinsey & Co.

Meyfroidt, Patrick, Thomas K. Rudel, and Eric F. Lambin. 2010. "Forest Transitions, Trade, and the Global Displacement of Land Use." *Proceedings of the National Academy of Sciences* (November 15). doi:10.1073/pnas.1014773107. http://www.pnas.org/content/early/2010/11/05/1014773107.

Muhammad, Andrew, James L. Seale Jr., Birgit Meade, and Anita Regmi. 2011. "International Evidence on Food Consumption Patterns: An Update Using 2005 International Comparison Program Data". Technical Bulletin TB-1929. Washington, D.C., USA: Economic Research Service, U.S. Department of Agriculture. http://www.ers.usda.gov/Publications/TB1929/.

Müller, Christoph, Alberte Bondeau, Alexander Popp, Katharina Waha, and Marianela Fader. 2010. "Climate Change Impacts on Agricultural Yields: Background Note to the World Development Report 2010". Background Note. Germany: Potsdam Institute for Climate Impact Research.

Nelson, Gerald C., Mark W. Rosegrant, Jawoo Koo, Richard Robertson, Timothy Sulser, Tingju Zhu, Claudia Ringler, et al. 2010. "The Costs of Agricultural Adaptation to Climate Change". International Food Policy Research Institute (IFPRI).

Nelson, Gerald, Mark Rosegrant, Jawoo Koo, Richard Robertson, Timothy Sulser, Tingju Zhu, Claudia Ringler, et al. 2009. "Climate Change: Impact on Agriculture and Costs of Adaptation." Food Policy Report. International Food Policy Research Institute (IFPRI).

Neumann, Kathleen, Peter H. Verburg, Elke Stehfest, and Christoph Müller. 2010. "The Yield Gap of Global Grain Production: A Spatial Analysis." *Agricultural Systems* 103 (5) (June): 316–326.

Reilly, J. M., J. Hrubovcak, J. Graham, D. G. Abler, R. Darwin, S. E. Hollinger, R. C. Izaurralde, et al. 2002. *Changing Climate and Changing Agriculture*. New York, NY: Cambridge University Press.

Reilly, J., S. Paltsev, B. Felzer, X. Wang, D. Kicklighter, J. Melillo, R. Prinn, M. Sarofim, A. Sokolov, and C. Wang. 2007. "Global Economic Effects of Changes in Crops, Pasture, and Forests Due to Changing Climate, Carbon Dioxide, and Ozone." *Energy Policy* 35 (11). Energy Policy: 5370–5383.

Reilly, John, Jerry Melillo, Yongxia Cai, David Kicklighter, Angelo Gurgel, Sergey Paltsev, Timothy Cronin, Andrei Sokolov, and Adam Schlosser. 2012. "Using Land To Mitigate Climate Change: Hitting the Target, Recognizing the Trade-offs." *Environmental Science & Technology* 46 (11) (June 5): 5672–5679. doi:10.1021/es2034729.

Al-Riffai, P., Betina Dimaranan, and David Laborde. 2010. *Global Trade and Environmental Impact Study of the EU Biofuels Mandate*. Washington DC: International Food Policy Research Institute. http://environmentportal.in/files/biofuelsreportec.pdf.

Roberts, Leslie. 2011. “9 Billion?” *Science* 333 (6042) (July 29): 540 –543. doi:10.1126/science.333.6042.540.

Rosegrant, M.W., C. Ringler, Tingju Zhu, Simla Tokgoz, and Prapti Bhandary. 2013. “Water and Food in the Global Bioeconomy: Challenges and Opportunities for Development.” *Agricultural Economics* forthcoming.

Rosenzweig, C., J. elliot, D. Deryng, A.C. Ruane, A. Arneth, K.J. Boote, C. Folberth, et al. 2013. “Assessing the Agricultural Challenges and Risks Posed by Climate Change in the 21st Century.” *Proc Natl Acad Sci US* Forthcoming.

Schlenker, Wolfram, and Michael J. Roberts. 2009. “Nonlinear Temperature Effects Indicate Severe Damages to U.S. Crop Yields Under Climate Change.” *Proceedings of the National Academy of Sciences* 106 (37): 15594–15598. doi:10.1073/pnas.0906865106.

Searchinger, Timothy, Ralph. Heimlich, R.A. Houghton, Fengxia Dong, Amani Elobeid, Jacinto. Fabiosa, Simla Tokgoz, Dermot Hayes, and Tun-Hsiang Yu. 29. “Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change.” *Science* 319 (5867): 1238–1240. doi:10.1126/science.1151861.

Steinbuks, Jevgenijs, and Thomas Hertel. 2012. “Forest, Agriculture, and Biofuels in a Land Use Model with Environmental Services (FABLE).” *GTAP Working Paper No. 71*. http://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=3988.

Steinbuks, Jevgenijs, and Thomas W Hertel. 2013. “Energy Prices Will Play an Important Role in Determining Global Land Use in the Twenty First Century.” *Environmental Research Letters* 8 (1) (March 1): 014014. doi:10.1088/1748-9326/8/1/014014.

Taheripour, F., C. Hurt, and W. E. Tyner. 2013. “Livestock Industry in Transition: Economic, Demographic, and Biofuel Drivers.” *Animal Frontiers* 3 (2) (April 1): 38–46. doi:10.2527/af.2013-0013.

Taheripour, Farzad, Thomas W. Hertel, and Jing Liu. 2013. “The Role of Irrigation in Determining the Global Land Use Impacts of Biofuels.” *Energy, Sustainability and Society* 3 (1) (February 28): 4. doi:10.1186/2192-0567-3-4.

Taheripour, Farzad, and Wallace Tyner. 2013. “Biofuels and Land Use Change: Applying Recent Evidence to Model Estimates.” *Applied Sciences* 3 (1) (January 11): 14–38. doi:10.3390/app3010014.

Tyner, Wallace E. 2010. “The Integration of Energy and Agricultural Markets.” *Agricultural Economics* 41 (6).

Westhoff, Patrick. 2010. *The Economics of Food*. New Jersey, USA: Financial Times Press.

White, J. W., G. Hoogenboom, and L. A. Hunt. 2005. “A Structured Procedure for Assessing How Crop Models Respond to Temperature.” *Agron J* 97 (2): 426–439.

White, Jeffrey W., Gerrit Hoogenboom, Bruce A. Kimball, and Gerard W. Wall. 2011. “Methodologies for Simulating Impacts of Climate Change on Crop Production.” *Field Crops Research* 124 (3): 357–368. doi:10.1016/j.fcr.2011.07.001.

World Bank. 2008. “Agriculture for Development.” World Development Report.

Ziska, Lewis H., and Jeffrey Dukes. 2011. *Weed Biology and Climate Change*. 1st ed. Wiley-Blackwell.