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The Global Supply and Demand for Agricultural Land in 2050: A Perfect Storm in the Making?[1]

AAEA Presidential Address

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Journal Version[2]

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Over the past three years, there has been a convergence of interest in the global farm and food system and its contributions to feeding the world's population as well as to ensuring the environmental sustainability of the planet. The 2007/2008 commodity crisis underscored the vulnerability of the global food system to shocks from extreme weather events, energy and financial markets, as well as government interventions in the form of export bans and other measures designed to avoid domestic adjustment to global scarcity. We have learned that a "perfect storm" in which all these factors coincide can have a devastating impact on the world's poor, as well as pressuring the world's natural resource base. As we look ahead to the middle of this century, will the world's agricultural resource base be up to the task of meeting the diverse demands being placed on it?

The number of people which the world must feed is expected to increase by another 50% during the first half of this century. 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, there are signs of slowing yield growth for key staple crops. 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 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 (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 (Gibbs et al.), or indirectly via a cascading of land use requirements with crops moving into pasture and pasture into forest (Barona et al. 2010).

Finally, agriculture and forestry are likely to be the economic sectors whose productivity is most sharply affected by climate change. This will shift the pattern of global comparative advantage in agriculture (Reilly et al. 2007), and may well reduce the productivity of farming in precisely those regions of the world where malnutrition is most prevalent, while increasing yield variability and the vulnerability of the world’s poor (Ahmed, Diffenbaugh, and Hertel 2009). In light of these challenges facing the global farm and food system, this Presidential Address will review the evidence on the future supply and demand for agricultural land[3] four decades from now and provide a critical evaluation of the potential for a perfect storm in land markets, worldwide.

Historical Perspective

Humans have been involved in inducing land cover change since the beginning of human history (Ramankutty et al., 2006). Foley et al. (2005) argue that most societies follow a common sequence of land use regimes, beginning with largely natural ecosystems, followed by frontier clearings for subsistence agriculture and small-scale farms, which in turn gives way to intensive agriculture, the development of urban areas, and the advent of land devoted to protected recreational activities and biodiversity. Today, about one-third of the world's land cover is devoted to agriculture, one-third to forests and one-fifth to savannas, grasslands and shrublands; the remainder is either barren or low productivity land, with urban areas comprising about one percent of the world's land cover (Navin Ramankutty 2010).

Ramankutty, Foley, and Olejniczak (2002) examine changes in cropland cover over the 20th century. They begin by plotting population against hectares of cropland in 1900 and observe that areas with high population also had larger cropland areas, with the global average cropland area equaling 0.76 ha/capita. Indeed, in 1900, most regions of the world fell quite close to this ray from the origin in their graph. By 1990, under the influence of greatly improved agricultural productivity, the slope of this line had declined by more than half, to just 0.35 ha/capita, and, while many regions still fall along ray from

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[3] Throughout this talk I will refer to both agricultural land as well as crop land. The reader should recognize that these are very different items, as the former typically includes pasture lands, which greatly exceed cropland in terms of physical hectares.

the origin, some have begun to deviate more sharply from this relationship. Both Russia and the US showed much stronger than average cropland area growth, relative to population, and both China and South Asia experienced the reverse, with relatively more rapid population growth. These divergences from the (1990) 0.35 ha cropland/capita line were enabled in part by falling costs of international transport and declining trade barriers, both of which have facilitated increased international trade in food products. They also reflect the inherent responsiveness of yield growth to population pressure (Hayami and Ruttan 1985).

Over the final two decades of the 20th Century, land cover change accelerated to unprecedented levels. Lepers et al. (2005) document these trends and highlight deforestation "hotspots". Most of these hotspots are in the tropics, with the Amazon leading the way, followed by Southeast Asia, Central Africa and Central America. Russia, too, shows some deforestation hotspots in their analysis. These authors also conclude that the areas with the greatest amounts of degradation – often from multiple sources – arise in the Middle East and near Asia. This degradation of existing crop land, when combined with the seemingly inexorable growth in demand for food, fiber and fuel has led many observers to suggest that the world may run out of land. Malthus (1888) is perhaps the best known champion of this position. However, he is by no means alone. It seems that every decade or two, the specter of the world running out of land is raised. As recently as 1985, Buringh wrote that "Recent studies show that on a global scale all land reserves will be lost within one century and reserves of highly productive land will be lost in twenty-five years." Well, here we sit, 25 years later, and we are far from this outcome. This highlights the difficulty of simply extrapolating from past trends. A more rigorous analytical framework is needed, which is the subject of the next section.

Economic Analysis of the Long Run Supply and Demand for Land

In discussing the research undertaken to date on the long run supply and demand for land, it is quite helpful to have an analytical framework in mind. This will permit us to better interpret and evaluate the results from the wide variety of studies now available on this topic. The simplest possible model of the long run supply and demand for land, while still having sufficient richness to reflect the major contributions to the literature on this topic, is developed in the on-line appendix. For the sake of simplicity, I collapse the demand for all agricultural outputs between the present day and 2050 into a single variable. The *percentage change* in demand for agricultural products has a price-sensitive element represented by the product of an elasticity and a percentage price change, $-\eta_A^D p_A$, wherein the price elasticity of demand captures the revenue-weighted average price responsiveness of all sources of demand, including food, fiber and fuel demands for agricultural output, to changes in the price of agricultural output, p_A. There is also an exogenous component, Δ_A^D, which captures potential shifts in the demand schedule, reflecting the percentage change in output, at constant prices, required to satisfy demands such as population growth and politically determined biofuel mandates which are largely exogenous to agricultural markets.

The model has one global production function which combines agricultural land with variable inputs to produce agricultural output. Variable inputs are deemed to be in perfectly elastic supply in the long run, whereas the long run supply of land to agriculture is significantly constrained. The potential for increasing yields in response to higher global prices for farm products – and hence higher returns to land – is captured by the elasticity of substitution between variable inputs and land. Assuming constant returns to scale (clearly inappropriate at the farm level, but a good fit for long run industry behavior under entry and exit), zero pure long run economic profits, and cost minimizing behavior, we obtain a long run derived demand for land, q_L^D, which is a function of three elements. The first is the expansion effect. All else constant, boosting the supply of agricultural output by 50% will require a 50% increase in effective (productivity adjusted) land. However, this land requirement may be diminished if there is an economic incentive for intensification of production. Such an incentive will arise when land becomes scarce, relative to other inputs. In the face of such scarcity, producers will substitute variable inputs (e.g., labor, fertilizer) for land, thereby raising agricultural output per unit of land, subject to the limitations of technology, as captured in the substitution elasticity. I will refer to this as the *intensive margin* of agricultural supply response, which may also be expressed as a function of agricultural prices: $\eta_A^{S,I} p_A$. Finally, I have also included the potential for exogenous yield growth (expressed as a percentage of global average yields), Δ_L^D, which enters into this derived demand equation with a negative sign; faster yield growth diminishes the global derived demand for land. This exogenous element is included, as many of the long run analyses reviewed below include an element of changing yields which is not determined by relative prices and therefore exogenous to this simple partial equilibrium model.

To complete the model, we must add another equation describing the long run supply of land to agriculture. As with aggregate demand, I include both a priceresponsive element, indicating that additional land will be converted to agricultural uses if the relative return to land used in agriculture rises; expressing this too as a function of agricultural prices, we have: $\eta_A^{S,E} p_A$; which is referred to as the *extensive margin* of supply response. This must also take into account the fact that new land entering the sector may be of lower quality than existing agricultural land. There is also an exogenous element in this supply equation, Δ_L^S, representing shifts in this land supply function. It describes the rate at which agricultural land is converted to other uses due to forces outside this simple model (e.g., urban sprawl).

The percentage change in the total supply response of agriculture to output prices may be written as the sum of the intensive and extensive margins: $q_A^S / p_A = \eta_S^A = \eta_A^{S,I} + \eta_A^{S,E}$. Solving this model for the long run equilibrium change in agricultural land use, q_L^*, as a function of the exogenous shocks to demand, land conversion, and trend yield growth we have the following equation[4]:

$$q_L^* = [(\Delta_A^D + \Delta_L^S - \Delta_L^D) / (1 + \eta_A^{S,I} / \eta_A^{S,E} + \eta_A^D / \eta_A^{S,E})] - \Delta_L^S \qquad (1)$$

When combined, the six arguments on the right hand side of this equation offer a complete method of organizing the arguments developed in the literature on long run agricultural land use. This expression also offers several immediate insights that will help us exercise our analytical understanding of the way in which these six elements interact. Firstly, if there is simultaneously no scope for intensification of production ($\eta_A^{S,I} = 0$) and

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[4] This model is fully developed in the longer, on-line version of this paper, available at http://ageconsearch.umn.edu/handle/92639.

no price responsiveness in demand ($\eta_A^D = 0$), then (e.g.) a 5% exogenous growth in demand, net of yield growth $(\Delta_A^D - \Delta_L^D)$ gets translated into an equilibrium rise of 5% in equilibrium agricultural land use. As we will see, this is a pretty accurate characterization of much of the biophysical literature on long run land use. The drawback of this approach is that it abstracts from the fact that such shocks might in fact lead to an *endogenous response* on the part of the farm and food system in the face of induced economic scarcity. This is where the price elasticities of demand and supply (and hence the contributions of agricultural economists) come into play.

By including the price responsiveness of yields and final demand, economic analyses of land use boost the size of the denominator in this expression for equilibrium land use change. In effect the potential for intensification of production and demand reductions serve as “shock-absorbers”, dampening the amount of land employed in agriculture over the long run in the face of the scarcity induced by net demand growth. Any outward shift in net demand boosts food prices, which, in turn tempers the realized demand for agricultural products. The ensuing rise in land prices serves to encourage the intensification of production, with agricultural producers substituting variable inputs for land to achieve higher yields.

A second important insight from (1) is that what matters from the point of view of equilibrium land use in agriculture is not the absolute size of the intensification and final demand elasticities, but rather their size *relative to* the land supply elasticity, $\eta_A^{S,E}$. If all three elasticities were equal in magnitude, then each of these margins of economic response would contribute equally to dampening the growth in net demand; only one-third of net demand growth would be translated into agricultural land use change. In addition to this increase, we would have to make an adjustment for land conversion (a reduction in equilibrium land use) from agriculture yielding the following net change in long run land use: $q_L^* = [(\Delta_A^D - \Delta_L^D)/3] - 2\Delta_L^S/3$.

I will return to expression (1) time and again throughout the paper, as we seek to understand either the implications of particular assumptions/omissions made in the studies considered, or alternatively, as we seek to back out the implications of results pertaining to the long run use of land in agriculture, as revealed by the simulation of large complex models.

Factors Shaping the Demand for Land in Agriculture

While one can debate which factors are best classified as "demand-side" and which may be viewed as operating through the "supply side", we will take our cue from the framework laid out in the preceding section. Thus the determinants of the *derived demand* for land consist of (a) population growth, rising per capita incomes, and all the attendant changes in food demand that accompany the increase in purchasing power (Δ_A^D), as well as the price-responsiveness of consumer demand for food (η_A^D), (b) bioenergy -- the potential for agriculture to become an important source of fuel, both for transportation as well as for heat and power (this bears on both exogenous demand growth, Δ_A^D, and on the price-responsiveness of demand, η_A^D, as will be discussed below (c) finally, productivity changes, both exogenous, Δ_L^D, and endogenous, $\eta_A^{S,I}$, will be considered, as they alter the *derived demand* for land.

<u>Population Growth:</u> When one thinks of the long run drivers of demand, population growth is generally the first one that comes to mind. In one of the key inputs for the recent CAST report on the future of world agriculture, (Tweeten and Thompson 2009) summarize recent UN projections of population growth and their implications for demand in 2050. The UN's medium growth scenario has population increasing by 50% between 2000 and 2050, from 6 billion to about 9 billion people. Under this demographic scenario, the annual growth rate in population will have diminished from 1.3% in 2000 to just 0.36% in 2050. And some plausible, low growth, demographic projections have population actually beginning to decline by 2050. Such declines have been foreshadowed by very sharp declines in fertility in Asia over the past 25 years where every nation (Malaysia excepted) with a GDP per capita of $3500 or more is now at or below replacement fertility levels (Southgate, Graham, and Tweeten 2010, table 11.2). This translates into a decline in the growth rate in the demand for land. However, the demand for agricultural output is not solely a function of population, it also depends importantly on how much each individual consumes, and the land intensity of their consumption goods. This brings us to the next demand driver.

<u>Income Growth:</u> Global growth in per capita food and fiber consumption due to income growth has been quite stable over the past 60 years, averaging about 0.27%/year (Buchanan, Herdt, and Tweeten 2010), but this growth has masked very different changes at the national level, with developed countries' growth rates slowing, even as the growth in per capita consumption in poor countries has accelerated. The latter phenomenon reflects the strong tendency for dietary upgrading as individuals meet their basic nutritional requirements. Increased consumption of livestock products greatly increases the underlying demand for farm output, as it takes more calories in the form of feedstocks to produce a calorie from livestock products. In their projections to 2050, (Tweeten and Thompson 2009) project continued growth in per capita demands for agricultural output of about 0.25%/year between 2000 and 2050, although they abstract from potential price effects.

Price Elasticity of Demand: Food demands are generally price-inelastic, particularly when viewed as an aggregate – and particularly when it comes to staple grains. Seale, Regmi, and Bernstein (2003) estimate an international cross section demand system and obtain own-price elasticities of demand for food, beverages and tobacco which may be viewed as long run consumption responses to permanently higher/lower prices. Their estimates are a function of per capita income and range from -0.65 in Tanzania, to -0.08 in the United States. In making long term projections, this suggests that the global demand elasticity for food (η_A^D) should be adjusted downward over the projections period. By 2050, the appropriate global value for this parameter is likely to be in the neighborhood of the average for present day high income countries (-0.27) as countries become wealthier over time.

Bioenergy and global land use: When food demand growth is coupled with growth in fiber and bioenergy demands, which Tweeten and Thompson (2009) assume to grow at 0.10%/year, this results in total agricultural demand growth of 0.71%/year over this 50 year period. This translates into an exogenous shock to agricultural demand (Δ_A^D) from 2000-2050 of 79%. This is comparable to FAO projections (Bruinsma 2009) for this period, which amount to a 70% shock based solely on food, feed and fiber demands. The difference between these two forecasts appears to be largely due to the assumptions about biofuel demands. This is an area which has dominated recent growth in agriculture demands – 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). However, this source of demand is highly dependent on uncertain policies as well as oil prices and deserves more detailed discussion.

Despite the rather long history of biofuels, it is only recently that the debate over global land use impacts has captured the public's attention. The United Nations Environment Programme (2009) estimates that total area under biofuels doubled between 2004 and 2008, when it reached 36 Mha. The demand for biofuel feedstocks has now become a major factor in global demand growth. Indeed, FAO/OECD (2008) projections for the coming decade suggest that it will account for 52% and 32%, respectively, of increased growth in global demand for maize and oilseeds. There have been several important drivers of biofuel growth, including regulations, subsidies and oil prices, and their relative importance varies across countries (Hertel, Tyner, and Birur 2008). We will discuss each of these factors in turn, assessing their potential for contributing to long run demand growth for land.

Biofuel mandates and land use change: Interest in the global land use impacts of biofuels reached international prominence with the publication of the Searchinger et al. (2008) paper which suggested that, rather than reducing GHG emissions as was previously assumed (Farrell et al. 2006), the use of corn ethanol in place of petroleum in the US liquid fuel mix might actually double GHG emissions when global land use change is taken into account. Analysis of the land use impact of biofuels represents a direct application of the framework laid out above, and may be usefully viewed in that light.

Clearly from equation (1), the impact of any exogenous growth in feedstock yields (Δ_L^D) will diminish the transmission of a given biofuels shock (Δ_A^D) to long run land use – although any such exogenous change would presumably take place independently of the biofuels shock and so is not a legitimate part of the biofuel impact study. On the other hand, the endogenous yield response to the biofuel shock, via the intensive margin of supply response ($\eta_A^{S,I}$) is central to the debate. One of the most controversial assumptions in the Searchinger et al. (2008) paper was to ignore this economic response. Hertel et al. (2010, table 2) explore the competing effects of the intensive and extensive margins of endogenous response on global average crop yields in response to US ethanol production. Utilizing the very limited available empirical information on these two elements of endogenous yield changes, they find that, globally, when the supply responses of all crops in all regions are considered, the yield increasing element dominates. Thus, ignoring this element will overstate the impact of biofuel growth on global land use.

Relatively little attention has been paid to the importance of the price elasticity of demand in moderating land use change due to the biofuels shock in the debate surrounding the Searchinger et al. estimates, yet it is clear from equation (1) that this is equally important. Hertel et al. (2010) evaluate the impact of eliminating the endogenous demand response to the biofuels induced scarcity in global food and agricultural markets, and find that, absent any price-induced consumption adjustments ($\eta_A^D = 0$), twice as much forest is converted globally as in their base case, and emissions from global land use change jump by 41%. In summary the two "automatic stabilizers" in equation (1) matter a great deal when assessing the global land use change following exogenous shocks to food, fuel and fiber demands.

Most of the regulatory studies of biofuels focus on the near- to medium-term impacts on global land use. However, the problems associated with indirect land use change notwithstanding, there is an expectation that biofuels could play a significant role in climate change mitigation policy for much of this century (Wise et al. 2009). How much could a large scale, global, sustained bioenergy program affect global land use? This is the subject of a recent paper undertaken by Fischer (2009) for the 2009 FAO food summit. I focus here on Fischer's "TAR-V1" scenario in which the mandatory, voluntary and indicative targets for biofuel use announced by both developed and developing countries are implemented by 2020 – boosting production to twice current levels. Second generation technologies are assumed to become available after 2015, and are only gradually deployed under this scenario. This results in 2020 cereal prices which are 38% above baseline, falling off to 27% above baseline by 2050, when second generation biofuels assume a larger share of the total. The price rise is widespread and crop prices increase by roughly a third in 2030 and 27% in 2050. This price rise boosts cultivated land globally by 48 Mha (about 2.8%) by 2050. The very strong price impact, and quite small increase in land supply, suggests rather inelastic supply elasticities in the long run.

We can use the simple analytical framework outlined above to gain further insight here. That model yields the result (see on-line appendix) that the long run equilibrium land price rise is equal to the net exogenous shock, divided by the sum of the three key price elasticities in the system:

$$p_A^* = (\Delta_A^D + \Delta_L^S - \Delta_L^D)/(\eta_A^{S,I} + \eta_A^{S,E} + \eta_A^D) \qquad (2)$$

The shock to global cereals demand from biofuels is about 13% in 2050 (Fischer 2009), giving rise to indirect estimates of the denominator in equation (2) equaling 0.48. Of course, other prices are also changing in this scenario, so these are more like total elasticities. Regardless, evidence that the sum of all three elasticities is less than 0.5 over a 40 year time horizon is rather striking.

Oil prices and the overall energy outlook: In the end the critical factor in determining the long run demand for agricultural land in bioenergy is likely to be the global oil price. Unfortunately, this is an area of great uncertainty. Recent EIA forecasts for global oil prices in 2030 range from a low of \$50/bbl to a high of \$200/bbl (Energy Information Agency 2010, Figure 36). If oil prices reach the high end of this forecast for a sustained period of time, we can expect massive increases in bioenergy production. On the other hand, at the low end of this forecast, enthusiasm for biofuels will likely diminish as existing plants are idled and investor interest shifts elsewhere. *So the future of agriculture may depend critically on developments outside the food system.*

This point is also highlighted in the recent CAST report on the future of agriculture, which refers to the high oil price scenario as one in which “the potential demand for farm output is nearly unlimited” (Buchanan, Herdt, and Tweeten2010, p.3). In terms of the analytical framework laid out above, this translates into a highly elastic demand for agricultural output. This point is underscored in a more concrete form in recent simulations of the FAPRI model (Meyer and Thompson 2010). Drawing on this work, Patrick Westhoff (personal communication) suggests that even the EIA forecast of expected oil prices, which reach $125/bbl in 2030, could have a dramatic impact on corn ethanol production in the US – which, under relatively conservative assumptions about production technology and trade, reaches 23.5 billion gallons per year in 2030, thereby accounting for 45% of US corn production.

Scope for increasing yields: Prior to the 20th century, most increases in agricultural output came at the extensive margin – from area expansion. However, this has changed dramatically over the past century (Ruttan 2002). Bruinsma (2009) decomposes the historical growth in world crop production from 1961-2005 and finds that 77% of this growth came through yield growth and 9% was due to increased cropping intensity, while just 14% of this historical growth was due to expansion in arable land area. Returning to the expression for equilibrium land use change (equation (1)), this would seem to suggest the possibility that the intensive component of the supply elasticity is larger than the extensive margin in the long run, i.e. $\eta_S^I > \eta_S^E$. Alternatively, this could be largely due to the significant productivity impact of public expenditures on agricultural research and development over the last century (Evenson, Waggoner, and Ruttan 1979).

In his projections to 2050, Bruinsma (2009) foresees an even larger share of this growth coming from the intensive margin, with just 9% of future crop output growth coming from area expansion. This reflects, in part, tightening constraints on global land and water availability (in terms of the model above, a reduction in the extensive supply elasticity). It also reflects greater optimism about the potential for yield growth in some of the poorest regions of the world where he finds significant yield gaps. This heavy reliance on the intensive margin for meeting the global demand for agricultural output has raised some concerns among researchers, as there is evidence of declining growth rates for agricultural yields over the past two decades. Ramankutty (2010, Figure 2.3) notes that wheat yields were growing at the rate of nearly 4%/year in the 1960s, but have fallen off to only 0.5%/year since 2000. Byerlee and Deininger (2010, Box 2.1) report that ten-year moving average growth rates for wheat and rice yields have declined from the 3-5% range in the mid-1980’s to just 1-2% in the most recent decade. Fischer, Byerlee, and Edmeades (2009) note that the growth of yield potential in two dozen “breadbasket” regions of the world has slowed to less than 0.5% annually. In the long run equilibrium view of the problem, as embedded in (1), this slowing of yield growth may simply be due to a slowing of net demand growth. This point is underscored by Alexandratos (personal communication) who examines the growth rate in yields, relative to the growth rate in demand over the last three decades and finds that, viewed in this light there is no evidence of slowing *relative* yield growth.

The recent slowdown in yield growth has also been attributed to a slower rate of growth in expenditures on agricultural research, as well as a diversion of existing funds away from yield-enhancing projects (Alston, Beddow, and Pardey 2009).[5] An alternative explanation for the slowing of yield growth is that producers in many regions of the world may be approaching their “yield potential”, making further closing of this “yield gap” increasingly difficult. Therefore a closer look at the potential for further intensification of production is warranted.

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[5] While yield growth drives the derived demand for land, total factor productivity (TFP) growth is key for prices; Fuglie (2008) shows that, contrary to yields, TFP growth has not slowed down in recent years.

A closer look at the yield gap: Lobell, Cassman, and Field (2009) review the literature on yield gaps, drawing on studies using a variety of different methods, including: simulations of crop growth models, field trials, and observations of maximum farmer yields. They find yields for global crops ranging from 20% to 80% of yield potential. In most major *irrigated* wheat, rice and maize systems, they find yields at or near 80% of yield potential, suggesting that further increases in yields may be more difficult in these regions. This is important since irrigated agriculture accounts for more than two-fifths of global crop production (Bruinsma 2009). In contrast Lobell, Cassman, and Field (2009) find that rain fed yields are commonly 50% or less of their yield potential.

Recently, a spatially explicit, global data set on crop yields and harvested area has become available (Monfreda, Navin Ramankutty, and Foley 2008) which has permitted researchers to assess the global yield gap for specific crops, based on a comparison of yields under specific agronomic and climatic conditions. This is in the spirit of the Lobell, Cassman, and Field (2009) survey category of studies comparing observed yields to maximum yields by other farmers – albeit comparing grid cell averages across the entire globe. Two papers utilizing this data set to examine the yield gap were available to me at the time of writing this paper. The first, by Licker et al. (2010), establishes a matrix of 100 different global climatic and agronomic conditions based on growing degree days and soil moisture availability. They then order grid cells based on observed yields (from lowest to highest yields) and cumulate harvested area within these “climate zones” until they reach the 90th percentile, the yield of which they use as their maximum potential yield estimate under current climate, technology and economic circumstances. They then compute the yield gap fraction as *(1 – Actual yield/Climatic potential yield)* by crop and grid cell and plot these results (Licker et al. 2010, figure 5). Yield gaps for maize are small in North America and Western Europe, but extremely large in Africa, and also quite large in Eastern Europe. For soybeans, yield gaps are low in the US Corn Belt as well as quite low in Brazil. Yield gaps for wheat are small in Western Europe, larger in the US and quite large in Eastern Europe and Russia. The authors also compute the potential for global production increases, based on currently harvested area, provided all grid cells reached their maximum climatic yield potential, as revealed in the current data base. These increases by crop are as follows: maize (50%), rice (40%), soybeans (20%), and wheat (60%), suggesting that, given the right incentives, much of the increased demand for cereals and oilseeds in 2050 could be met using existing technology.

Given the considerable potential for global yield increases on existing lands, the question arises: What would it take to close this yield gap? This is addressed by the second paper using the Monfreda, Ramankutty, and Foley (2008) data set. Neumann et al. (2010) estimate a frontier production function for global grain production in which the climatic and agronomic variables set the frontier for each grid cell, and a variety of physical and socio-economic variables are used to explain deviations from this frontier. The latter include: irrigation, slope, labor force (population) density, accessibility to markets, and a so-called “market influence” variable. Not surprisingly, their results suggest that the constraining factors (causes of deviations from potential yields) vary considerably by region. Figure 4 in Neumann et al. (2010) highlights the regions with very low efficiency for wheat, maize and rice, and links these with the predominant constraints in the region. For example, in the case of maize throughout the Guinea-Savanna zone of Africa, they identify market influence and accessibility as key constraints. This is in agreement with recent analysis of that same region by the World Bank (2008), which concludes that poor infrastructure and high transport costs impede the effective demand for land in much of sub-Saharan Africa.

Probably the most comprehensive study of yield gaps to date was undertaken by the International Rice Research Institute (1979). Robert Herdt, a lead author in this work, summarizes their findings as follows: “the overall weight of the evidence examined suggests that it is relatively easy to account for the dramatic gap between what is technically possible and what has been achieved: what is technically possible is more modest than most observers admit; the economics of substantially higher yields is not attractive (p.421).” This brings us to the question of commodity prices and the scope for farm response to higher prices which may arise out of scarcity or improved connections to international markets.

There is a vast agricultural economics literature on yield response to commodity prices ($\eta_A^{S,I}$ in terms of the framework laid out above). In a recent survey of the evidence for corn in the US, Keeney and Hertel find evidence of the yield response to price in the US declining over time, with values in the range of 0.7 during the post-War period dropping to 0.2 in the more recent studies. Is this decline due to a narrowing of the “yield gap”? Or is it perhaps indicative of the increased homogeneity of producer behavior, which therefore leaves less scope for compositional changes? These hypotheses deserve further exploration.

Fertilizer as vehicle for increasing yields: For much of the world’s crop production, soil nutrients are a limiting factor in production, and therefore a potential contributor to observed yield gaps. Potter et al. (2010) have constructed a spatially explicit, global fertilizer and manure applications data base and their findings are quite instructive. They report average nitrogen fertilizer application rates of *less than 2.5 kg/ha* on more than 50% of global cropland. And *just 8.5% of the grid cells* fertilized with nitrogen show application rates in excess of 36 kg/ha and together *account for more than 50% of global N applied*! Clearly raising application rates on the other 91.5% of fertilized area could do a great deal to boost global production. However, high transportation costs and poor access to credit are often significant barriers to fertilizer use in much of the developing world. In short, this is further evidence that there is substantial scope for *endogenous* intensification of production in response to increased scarcity – particularly in the Africa and Latin America, where fertilizer application rates are currently very low.

Environmental constraints to intensification: Of course increased fertilizer use brings with it environmental consequences. On the extensive margin, nitrogen fertilizer applications have important consequences for regional climate, as well as global climate through the release of greenhouse gases (Houghton 1994). At the intensive margin, agricultural runoff and excess nitrogen and phosphorous has resulted in additional GHG emissions as well as the eutrophication of waterways (Vitousek et al. 2009). Given the expectation that the bulk of the additional agricultural production demanded between now and 2050 will come from this intensive margin, might the environmental impacts become a binding constraint? And if it does, what is the environmental trade-off between the intensive and extensive margins of agricultural expansion?

As with most of these problems, the primary issue is not one of global environmental quality, rather it varies greatly by locality. Potter et al. (2010, figure 7) examine the rivers and coastal zones affected by eutrophication and find that these are highly correlated with watersheds draining crop areas with extremely high nitrogen fertilizer application rates. This is to be expected as Seto et al. (2010) point out that nitrate leaching increases exponentially with higher application rates. While excessive application of fertilizer in certain parts of the world is creating serious environmental problems, much of the world is applying insufficient fertilizer to maintain soil quality. Further, this heterogeneity in application rates is even found at the scale of individual states in the US (Hertel, Stiegert, and Vroomen 1996). And it is compounded by the simultaneous application of manure on many fields that are also receiving commercial fertilizer applications (Beckman et al. 2009). This leads Seto et al. (2010) to propose a global rebalancing of fertilizer use, with targeted reductions in the most heavily fertilized regions, even as it is increased in other parts of the world.

Scope for shifting out the yield frontier: Up to this point the discussion has largely focused on increasing yields, given current technology. However, there is considerable potential for shifting the frontier outward. Part of this response will be governed by scarcity, as high land prices convey the message to public and private sector researchers that higher yields are desirable (Hayami and Ruttan 1985). Part of this response will be governed by the regulatory environment. This is nowhere more evident than in the debate over the use of genetically modified organisms (GMOs) in agricultural production which has constrained the adoption of yield-increasing technologies in many parts of the world (Paarlberg 2008).

Spatial issues in global demand: Because demand is global, but the supply of land is local, international trade has become increasingly important as a mediator between the two. As noted previously, Ramankutty, Foley, and Olejniczak (2002) highlight the geographic divergence of arable land and population growth over the course of the 20th century as global trade in farm and food products became increasingly important. Golub and Hertel (2008) explore this issue with regard to the future pattern of global land use. Specifically, they examine the impact of increasing economic integration over the period 1997-2025 on global agricultural land use. Such integration is expected to significantly boost farm land cover in the Americas, as well as in Australia and New Zealand, relative to a baseline scenario in which no further integration is permitted. Climate change is likely to further boost the importance of international trade as a mediator between the more heavily and less heavily affected regions of the world (Randhir and Hertel 2000).

Factors Shaping the Supply of Land to Agriculture

Having developed some of the key demand side factors, we now turn to the supply of land to agriculture. Here, we are concerned, both with the largely exogenous (to agriculture) factors contributing to the availability of land for farming (Δ_L^S), such as urbanization, demand for lands for preserving biodiversity, and climate change, as well as the anticipated endogenous response to signals of increasing scarcity (η_S^E). We expect that land, as well as water availability for irrigation purposes, will be forced to compete with other uses, including forest products, carbon sequestration, as well as other environmental services for which payments might be offered.

Urbanization: In terms of the simple analytical model summarized in equation (1), urban sprawl is treated as an exogenous shift in the supply of land to agriculture (Δ_L^S). United Nations' projections suggest that all incremental population growth between now and 2050 – about 3 billion people -- will translate into additional urban growth (Seto et al.

2010). Seto et al. (2010) argue that such urban expansion poses “one of the biggest environmental challenges for the 21st century” (p. 87), in part because cities are typically established in areas of prime farmland. Those authors start by assuming that average urban population densities of middle/low income countries (7500 people/sq km) will apply to the additional urban growth, resulting in an additional 400,000 sq km of urban land (slightly larger than Germany). This figure is nearly twice as large if the new urban areas are more representative of the global average urban density (just 3500 people/sq km). Of course, urban land currently covers less than 1% of the earth’s land surface (Houghton1994) so even this dramatic expansion has only a modest impact *in aggregate*. However, Byerlee (personal communication) argues that, while the effect of urban expansion will be relatively modest when viewed relative to the global availability of land, urbanization will be an important force in particular regions -- creating strong pressure on the availability of agricultural land in China and India in particular.

Biodiversity and the demand for eco-system services: Another source of exogenous land supply shock is the removal of land from commercial production for parks, other natural areas and the preservation of biodiversity. Ecologists estimate that clearance of land for agricultural uses has already reduced the extent of natural habitats on potential farm lands by more than 50% (Green et al. 2005) and the impact is currently being felt most strongly in developing countries. The debate over setting aside lands for biodiversity fits into the broader debate about the evolution of the demand for environmental services as economies become wealthier. Empirical evidence on the demand for environmental services generally supports the idea of an environmental Kuznets curve by which the demand for environmental amenities initially declines as countries seek to meet basic needs, eventually turning the corner at middle income levels from which point the demand for environmental amenities begins to rise relatively rapidly (Barbier 1997). Currently many developing countries lie to the left of this turning point, suggesting that the demand for environmental services has yet to fully materialize in many parts of the world.

Recently there has been a surge of interest in Payments for Environmental Services (PES) by which those seeking to preserve biodiversity and terrestrial carbon stocks. There is little doubt that the demand for such environmental services will grow over time, and this is likely to prove contentious in particular regions. However, abstracting from the demand for carbon sequestration, which will be discussed in the next section, this is unlikely to be a dominant force between now and 2050. In its recent review of PES, the Food and Agriculture Organization of the United Nations (2007, p.45) concludes that the development of biodiversity markets will be hindered by three factors: (a) highly uncertain benefits arising in the distant future, (b) difficulty in defining relevant measures of biodiversity for purchase in such markets, and (c) debate over the value of expending scarce biodiversity funds in agricultural settings where native biodiversity has already been degraded.

Green et al. (2005) raise the possibility that the best way to preserve biodiversity may be to farm existing lands more intensively. This so-called “land-sparing” strategy towards environmental conservation has introduced a new wrinkle into the biodiversity debate. It reflects an inherent appreciation of equation (1) which suggests that, by inhibiting intensification of agricultural production, regulators diminish the size of $\eta_A^{S,I}$, which in turn increases q_L^*. That is, environmental advocates may unwittingly generate greater biodiversity losses by forcing more expansion at the extensive margin.

Climate change: Climate change is also expected to play a significant role in the global availability of effective land for agriculture in the coming decades. The interplay between climate change and the farm sector is extraordinarily complex. Land use change associated with agriculture has a significant impact on local and global climate; meanwhile, changes in temperature and precipitation are likely to have an important impact on the productivity of land in agriculture. This has led those interested in climate change mitigation to turn their attention to agriculture and forestry for potential low cost mitigation options (Wise et al. 2009). However, most such options involve either removing land from agriculture, or lessening the intensity of agricultural production. All of these elements have the potential to contribute to a “perfect storm” of the sort alluded to in the title of this paper. We now turn to a consideration of each of these, in turn.

Climate Impacts on Agriculture: Nelson et al. (2010, table 4) report estimates of climate change induced yield effects in 2050 based on two of the leading global climate models -- with and without the effects of CO2 fertilization. The latter is a potentially favorable, but rather uncertain feature of increased GHG concentrations’ impacts on plant growth. They find that, in developing countries “yield declines predominate for most crops without CO2 fertilization. Irrigated wheat and irrigated rice are especially hard hit…. For a few crops, climate change actually increases developed country yields” Nelson et al. (2010, p.4). South Asia is the region with the greatest decline in climate-induced yields in their study. Sub-Saharan Africa and Latin America show mixed results. When incorporated into the IMPACT model of global food production and consumption, these yield shocks generate some dramatic price changes in the absence of CO2 fertilization – particularly for wheat (in the neighbourhood of 100% price rises) and maize (more than 50% rise, relative to baseline). These very large price changes in the face of relatively modest shocks to yields and harvested areas, suggest rather inelastic long run supply and demand behavior. Applying equation (2) to the price changes from the NCAR-NoCF scenario, along with yield and area shocks, we obtain estimates of the sum of the long three elasticities ranging from roughly 0.3 for wheat and maize to about 0.6 for rice.

Fischer (2009, table 4.4) finds that, with CO2 fertilization present, but without adaptation, expected 2050 rainfed cereal yields fall by nearly a third in Southern Africa due to climate change as predicted by the Hadley model, followed by declines in North Africa (-8%), and Central America (-2%). The effects in other regions are positive, with global average cereal yields rising by about 3%. In contrast, without CO2 fertilization, rainfed cereal yields drop by 5% using the Australian model and no-CO2 fertilization, with global prices rising by 10%. Using equation (2), this suggests that the sum of all three elasticities in Fischer's long-run economic model may be about 0.5 for cereals taken as a group – a figure consistent with the biofuels example discussed previously.

David Lobell and his varied collaborators have taken a wide range of approaches to assessing the impacts of climate on agricultural productivity. He has been a strong advocate of presenting a distribution of possible outcomes, noting that the uncertainty in steps (1) – (3) means that the true realizations could be quite different from our expected outcomes. Hertel, Burke, and Lobell (2010) capitalize on this wealth of experience and synthesize estimates of most likely yield changes, pessimistic outcomes and optimistic outcomes of climate change impacts on yields for 2030. In the most likely case, global productivity impacts are modest and positive for rice, wheat and oilseeds, but negative for maize – with the strongest adverse impacts being for maize in South Africa and the US. In the most optimistic scenario, global productivity impacts are positive for all crops globally, and only slightly negative in the worst-affected regions. However, if GHG concentrations increase faster than expected, and if their impact on temperature is more severe, with little gain from CO2 fertilization, then these authors suggest that the adverse yield impacts in 2030 could be significantly negative.

Schlenker and Lobell (2010) estimate the impacts of climate change on agriculture in Sub-Sahara Africa in 2050 using panel data and find that maize is most severely affected while millet is least affected by climate change. Nearly all countries in the region experience yield losses in the expected scenario, with overall losses for cereals and oilseeds in the range of 10%; in the worst case outcome (5% probability), yield losses for most cereals and oilseeds in Southern Africa exceed 50%. Overall, Lobell (personal communication) concludes that the agricultural impacts of climate change are likely to be: “not as bad as some claim, yet worse than many think they will be.” Further, he points out that, while climate change is unlikely to reverse the overall yield growth discussed above, “each 1 degree C rise in temperature is likely to result in a 5-6 year setback in trend yield growth.” This is significant, particularly in those regions with large numbers of malnourished people. Furthermore, recent research by Schlenker and Roberts (2009) suggests that there may be significant non-linear threshold effects for some crops which could lead to much more severe damages as the impacts of high temperatures accumulate.

Agricultural impacts on climate and GHG mitigation: The notion that agriculture and forestry are important for climate change is reinforced by recent estimates of the contribution of these sectors to global GHG emissions. Baumert, Herzog, and Pershing (2009) estimate that 13.5% of global GHG emissions derive directly from agriculture, and 18.2% from land use change, much of which is tied to agriculture as well. This has led to a proliferation of proposals aimed at involving these sectors in mitigation policies. Such actions are likely to have implications for the global supply and demand for land in 2050, and we turn now to this issue.

McCarl et al. (2007, p. 238) find that afforestation and biofuel production are the predominant sources of land-based mitigation in the US at low carbon prices (between $15 and $30/tonne CO2eq). Under climate legislation currently being considered in the US, McCarl (2009) estimates a loss in the year 2050 of nearly 50 million acres of cropland to forest cover in response to sequestration incentives. Not surprisingly, he finds that this has a very significant impact on US commodity prices, with corn prices rising by about 50% over baseline, leading to export declines across a range of agricultural commodities. In similar long run analysis conducted at the global level, Sohngen (2010) estimates that forestry could accomplish roughly 30% of total abatement over the next century, if the world were to follow an optimal carbon strategy. Such a strategy would increase global forest area by 900 Mha relative to Sohngen's baseline economic scenario for the next century.

Irrigation and Water availability: Water is an essential input for agricultural production. While the majority of crop land cover is rainfed, irrigated areas are considerably more productive and account for about 42% of global crop production – 47% in developing countries Bruinsma (2009, table 5). This is also evident in the fact that the absence of irrigation is estimated to play a key role in limiting potential yields of wheat, maize and rice in parts of the Americas, Africa and Asia (Neumann et al. 2010, figure 4). However, agriculture alone accounts for about 70% of freshwater withdrawals in the world. So clearly the availability of water for irrigation cannot simply be taken for granted, and this availability is a critical piece of the supply side of the global land use balance. Indeed, McKinsey & Co (2009) offer a detailed assessment of the water puzzle for the year 2030. They start at the river basin level and calculate water demand based on current technology and expected growth in agricultural and industrial output as well as population. In the absence of efficiency gains, they estimate that water demand will exceed existing sustainable, reliable water supply by 40% in 2030. Furthermore, this global gap masks much more serious water gaps at the level of individual river basins. They estimate that one-third of the world's population in 2030 will live in basins where the projected gap is greater than 50 percent. In summary, it appears that water for agricultural irrigation will become much more expensive in the future – no doubt spurring considerable efficiency gains, but also raising the cost of production and further limiting the amount of land on which crops can be economically grown.

Endogenous supply response in the long run: Most of the preceding factors influencing land supply in the long run may largely be considered as falling into the category of exogenous shocks to land availability for agriculture (Δ_L in the terminology of equation (1)). While the extent of urban sprawl might be influenced by agricultural prices, it is by-and-large an independent phenomenon – and similarly with the demand for land for parks/biodiversity, as well as the impacts of climate change. However, there is also potential for the supply of agricultural land to respond to scarcity – the so-called extensive margin of supply, η_S^E. Despite the importance of this parameter in determination of long run agricultural land use, estimates of its value are spotty, at large scale and particularly in the very long run.

The elasticity of land supply with respect to commodity price is implicit in the results produced by the global economic models so we can “back it out” of the reported findings using equation (2). In the case of the Fischer (2009) analysis of climate change and biofuels growth on world agricultural markets, we obtain an arc-elasticity of supply response with respect to aggregated crop prices of 0.075.[6] However, the implied responsiveness to relative returns to land in agriculture is actually quite a bit smaller. This is because we expect that the commodity price rise will be capitalized into land rents in the long run. Assuming labor, capital and other variable input prices are not affected by the biofuels-climate scenarios (although they may well change in the baseline, we are looking here at deviations from baseline), and if the returns to land and water represent one-third of total costs, then the implied elasticity of cultivated area with respect to cropland returns is just 0.025. This is comparable in size to the multi-year elasticities calculated by Barr et al. (2010) based on actual US cropland response over the recent commodity boom period.

It is possible to move beyond speculation and back-of-the envelope calculations in the case of specific countries. Lubowski, Plantinga, and Stavins (2006) capitalize on two decades of National Resources Inventory data points in the United States to estimate

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[6] Under the Hadley A2, TAR-V1 scenario, without CO2 fertilization, the arc elasticity is: (58ha/1727ha)*100%/45% = 0.075. Picking a more modest scenario: Hadley A2, TAR-V3 in 2050, wherein the 2050 price rise is just 15%, eliciting a 27Mha rise in cultivated area, we obtain and elasticity of 0.10.

the responsiveness of land transitions to changing rental rates. Ahmed, Hertel, and Lubowski (2008) have utilized this econometric model to compute the partial elasticity of US cropland supply in response to a perturbation in cropland rental which grows over time -- from 0.05 after 5 years to 0.28 after 50 years. Viewed in this light, the elasticities implied by the IIASA model would appear to be near term elasticities, not long term elasticities. This view is further strengthened if one refers to those studies utilizing cross-section data to look at land use change (Sohngen and Brown 2006).

Critical Assessment: Can we expect a perfect storm?

In their recent report on the future of global agriculture, CAST suggested that "numerous factors are converging to make 'the perfect storm' in global food and agriculture" (Buchanan, Herdt, and Tweeten 2010, p.12). The associated arguments are compelling: the global farm and food system will be asked to feed several billion more people, fuel millions of vehicles, supply power for electricity, supply fiber to the global textile industry and sequester carbon to mitigate climate change, all while yield growth is slowing, agricultural land is being degraded and/or removed for urban uses, and water is becoming increasingly scarce. Such concerns have been further reinforced by the rush on the part of foreign investors to invest in large scale developments of agricultural land in Africa and Latin America (Byerlee and Deininger 2010). In order to put this debate in perspective, this paper examines these changes in the context of a long run equilibrium in which prices adjust to equate supply and demand – *the question is not whether sufficient land will be available for agriculture, but rather: What will be the ensuing price?*

As we have seen, the prices at which this "perfect storm" in the global land markets will be resolved depend critically on the long run supply and demand elasticities in agricultural markets. Agricultural economists have spent the better part of the past century studying these relationships and I believe that we have important contributions to make to the debate over the long run sustainability of agriculture and the global environment. However, I fear that much of this rich knowledge has not yet worked its way into the global models being used for long run analysis of climate, biofuels and agricultural land use. Evidence presented in this paper from several of the most prominent long-run global agricultural models suggests that the supply and demand elasticities currently in use are geared towards the near term and ascribe most of the long run economic dynamics to exogenous factors, with "trend yield growth" being the most prominent amongst these factors. By adopting near term elasticities in their models, authors may be able to replicate particular short run "crises" in commodity markets, but it is not clear that the resulting models are well-suited for the kind of long run sustainability analysis envisioned here. This is not dissimilar to a problem faced by global ecologists who are just now seeking to reconcile what they know about high frequency (fast-moving) ecosystem interactions with low frequency (slow-moving) relationships (Carpenter and Turner 2000). The tendency to date has been to focus readily observed, high frequency events, while neglecting some of the important factors which drive the long run dynamics of the system.

Another important conclusion to this review is that the "perfect storm", should it arise in 2050, will not be a global phenomenon; rather, it will consist of many localized "storms". This stems from the fact that, while demand is increasing global, the land is, by definition, immobile, and, as documented in this paper, its biophysical and environmental characteristics are extremely heterogeneous. Therefore, assessment of the long run sustainability of agricultural land use necessarily requires a high degree of spatial resolution. Fortunately, the data bases and software tools for undertaking spatially resolved analysis of these long run drivers of land use change are now widely available. However, there remain significant barriers to entry in this field of study. I believe there will be high returns to public investments in open-source, data base infrastructure for explicitly spatial, global analysis of long run issues related to agriculture and its links with the environment. This is one of the objectives which I outlined in my AAEA Presidential election platform and I intend to pursue it vigorously over the coming year.

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