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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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Long Version, with Technical Appendix

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I. Motivation

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 putting considerable pressure on the world's natural resource base. As we look ahead to the middle of this century, will such commodity price spikes become more commonplace? 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, 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 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). Limiting the conversion of forests to agricultural lands is also critical to preserving the planet’s biodiversity (Green et al. 2005).

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 (J. 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[2] four decades from now and provide a critical evaluation of the potential for a perfect storm in land markets, worldwide.

II. **Historical Perspective**

Before looking ahead 40 years, it is useful to look backwards in time to gain an historical perspective on the issue of long term land use change around the world. A great deal has been written about patterns of global land use. In this paper, I draw heavily on the work of Navin Ramankutty and his colleagues in the fields of geography and ecology, who have written extensively on historical patterns of land use. Ramankutty et al. (2006) point out that people have been involved in inducing land cover change since the beginning of human history. Large scale burning of the landscape in western Africa was documented as early as 500 BC (Stewart, 1956, p. 119).

Foley et al. (2005) note 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. The world's present day land cover is clearly at many different points along this continuum, although the portion of the globe devoted to intensive agriculture, managed forestry, protected lands and urban areas has clearly been growing with time. Today,

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[2] Throughout this talk I will sometimes refer to agricultural land and other times to 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. When discussing specific findings I will endeavor to be careful to specify which one I have in mind.

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).

Focusing on crop land cover changes over the 20th century, Ramankutty, Foley, and Olejniczak (2002) document very different patterns of growth across the major regions of the world. In Europe, cropland cover actually declined over this century, and the cropland increases in the US, East Asia and tropical Africa were relatively modest. However, cropland cover expanded dramatically over the 20th century in Latin America, Canada, Australia and Southeast Asia. These authors also plot 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 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 in the *Philosophical Transactions of the Royal Society of London* 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.

III. **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 technical 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.

There is one global production function for agricultural output in this model. This combines agricultural land with variable inputs (including labor, capital, fertilizer, etc.). The latter 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. [3]

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 price-responsive 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

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[3] I believe that in the very long run, even trend growth in yields is itself function of price. Consider the following thought experiment: What if the price of agricultural output were zero? Would be expect to see continued growth in yields? On the other hand, consider the huge investments made in R&D related to corn yields over the past few years as corn prices reached record levels. Clearly prices matter – particularly in the very long run.

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:

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

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 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 (and indeed the long run activities of the agricultural research establishment) 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 (i.e., the extensive margin of land use), $\eta_A^{S,E}$. If, by some accident of fate, all three elasticities were equal in magnitude, then we would have the result that each of these three 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.

IV. **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. We will also consider the spatial distribution of such demand growth in this section, since the location of demand shocks can be equally important as their aggregate size.

Population Growth: 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 Stanley 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.

Income Growth: 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 Stanley Thompson 2009) project continued growth in per capita demands for agricultural output of about 0.25%/year between 2000 and 2050, although these demands will also depend to some degree on agricultural prices, which they do not consider.

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 (2008) 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.

Human use of bioenergy is as old as our ability to harness fire for heat and cooking. More recently, biofuel for transportation has become an important source of demand for feedstocks, and hence a source of derived demand for land in agriculture. The first country to embark on a serious biofuel program was Brazil, which is the world's leading global producer of sugarcane, the primary input for ethanol in that country. In early 2008, ethanol consumption exceeded gasoline consumption, marking the arrival of bio-based fuel as the primary source of liquid fuel for transport in Brazil (Zuurbier and Vooren 2010).

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, reaching 36 Mha (8.3 Mha in the EU, 7.5 Mha in the US and 6.4 Mha in Latin America). 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. This substantial growth arises, despite the discouraging of use of food products for biofuel production in a number of countries, including India and China. There have been several important drivers of biofuel growth over the past decade, 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 in *Science* 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 viewed over a 30 year time horizon. The reason for this difference in GHG emissions was the one-time release of carbon associated with the conversion of pastures and forest to cropland. Release of this finding led the California Air Resources Board (CARB), to include global land use change in their calculations of total GHG emissions associated with biofuels. CARB calculates its subsidy for low carbon fuels based on estimated emissions reductions which, in turn, are heavily influenced by land use change estimates. With such substantial economic incentives at stake, and with the US-EPA also required to consider land use impacts into account in the recent Renewable Fuels Standard, this set in m33otion a series of studies and expert panels assessing the land use impacts of biofuels. These studies represent a direct application of the framework laid out above, and may be usefully viewed in that light.

A first issue is the speed with which yields are expected to grow over the "baseline" period during which biofuels are phased in. 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 are not a legitimate part of the biofuel impact study. The potential for continued yield growth will be explored in more detail below. Here, I focus on the question of endogenous yield response to the biofuel shock, via the intensive margin of supply response ($\eta_A^{S,I}$). One of the most controversial assumptions in the Searchinger et al. (2008) paper was to ignore this economic response. The argument made by the authors of that study was that, while there was indeed potential for yields to increase in response to the scarcity induced by biofuels, this would be offset by the relatively lower yields on land brought into production at the extensive margin. (The framework laid out above treats this as a supply-side issue, and accounts for this by considering land supply as a quality-adjusted variable.) (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.[4]

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). The idea of investing in alternative energy sources which: (a) potentially reduce GHG emissions, (b) boost rural incomes, and (c) reduce reliance on imported oil, presents a potent mix of political opportunities, and many countries have proposed such programs (Renewable Energy Policy Network for the 21st Century 2009; Energy Information Administration 2009).

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[4] Of particular note is the important role in their findings played by supply response in the rest of the world (non-biofuel producing regions) and for the non-feedstock crops. To the extent that global yields in all crops rise a bit in response to the increased demand for biofuels, the global incentive to expand crop land area is greatly diminished.

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 crops prices increase by roughly the same amount as do cereals (35% in 2030 and 27% in 2050). This price rise boosts cultivated land globally by 38 Mha in 2020 and 48 mill ha (or 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. This is important, since price increases of this magnitude could have a significant impact on global poverty (Ivanic and Martin 2008).

We can use the simple analytical framework outlined above to gain further insight here. That model yields the result (see 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 15% in 2030 and 13% in 2050 (Fischer et al., 2009), giving rise to indirect estimates of the denominator in equation (2) equaling 0.4 in 2030 and 0.48 in 2050.[5] Of course, other prices are also changing in this scenario, so these are more nearly total elasticities for crops, or indeed all of agriculture. Regardless, evidence that the sum of all three elasticities is less than 0.5 over a 40 year time horizon is rather striking. We will return to this issue below.

Oil prices and the overall energy outlook: In the end, government budgets are finite, second generation biofuels have yet to reach commercial scale, and enthusiasm for biofuels which compete with the food supply has been on the wane. So the critical factor in determining the long run demand for agricultural land in bioenergy is likely to be not government mandates, but rather the path of global oil prices. 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. Thus, *the future of this sector 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 Tweeten, 2010, 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 Wyatt Thompson 2010). Drawing on this work, Patrick Westhoff (personal

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[5] Cereal consumption in 2030 and 2050 in the absence of biofuels is 2928 and 3388 Mtons, respectively. Biofuels demand under TAR-V1 is 437 in 2030 and 446 in 2050. So the cereals shocks to demand are roughly 15% (2030) and 13% (2050), respectively.

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.

Of course, just as equation (1) highlights the important role of supply and demand elasticities in providing automatic stabilizers for global agricultural markets, so too, do these factors play an important role in world energy markets. Sustained high oil prices would likely bring forth substantial new supplies of oil as well as great interest in substitutes for petroleum, including, but by no means limited to biofuels. There would also likely be a significant decrease in petroleum demand, as has been seen in the context of recent oil price spikes. All of these factors will serve to moderate any price increases over time.

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 over the 1961-2005 period 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. For example, in Sub-Saharan Africa, where yield growth accounted for just 38% of output growth over the past 45 years, Bruinsma foresees yield growth accounting for 69% of future growth. He also foresees large increases in cropping intensities in Latin America and East Asia – once again indirect evidence of the dominance of the intensive over the extensive margin of supply response. 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).[6] 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 gap increasingly difficult. Therefore a closer look at the potential for further intensification of production is warranted.

A closer look at the yield gap: Given the importance of future yield increases in delivering the agricultural production levels which may be demanded in 2050, it is quite natural to ask the question: How far are current producers away from the maximum attainable yield (yield potential) under current technology? 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. Viewed from this perspective, FAO projections of a stable share of production coming from irrigated land may be unrealistic. This issue will be further discussed below in the context of the supply-side of the story.

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[6] 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.

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). The pattern of yield gaps varies considerably by crop. 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.[7]

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[7] Bruinsma (2009) performs a similar exercise using the FAO/IIASA Global AEZ framework in order to isolate the

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 (2009) which concludes that poor infrastructure and high transport costs impede the effective demand for land in much of sub-Saharan Africa. Neumann et al. (2010) also find that market influence and irrigation are critical constraints in Central America and South Asian maize production. (The issue of irrigation will be discussed further below.)

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

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“transferable” portion of existing yield gaps. Controlling for crop variety and AEZ characteristics, he computes the maximum attainable yield in each country and compares this to average yields for rainfed wheat. With a few exceptions, the differences between attainable and actual average yields are quite substantial in most of the countries examined. In Argentina, for example, average actual yield is 2.6 t/ha vs. 4.6 t/ha attainable yield. In the Ukraine, this gap is even larger (2.5 t/ha vs. 7.1 t/ha attainable).

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). Keeney and Hertel (2008) offer a recent review of this literature in the context of the debate over indirect land use impacts of biofuels. As we have seen above, strong supply response at the intensive margin limits the equilibrium increase in global land devoted to crops in response to an exogenous increase in demand. Thus this was a contentious parameter in the land use and biofuels debate, with environmental interest groups arguing for a low value (thereby maximizing the land use change and hence GHG emissions), and industry groups suggesting that it is much larger (thereby minimizing GHG emissions from indirect land use change). Interestingly, Keeney and Hertel find evidence of the corn 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 deserves 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, both at the extensive and intensive margins (Navin Ramankutty 2010; Tilman et al. 2002; Foley et al. 2005). On the extensive margin, nitrogen fertilizer applications have important consequences for regional climate, as well as global climate through the release of greenhouse gases (R. A. 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 this aspect 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. And 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 and innovation responds (Hayami and Ruttan 1985). And 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.

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).

V. **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 (i.e. rural areas will not add any more total population) (Seto et al. 2010). So the key question becomes: What will be the average population density of these urban areas? 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 (Houghton, 1994) 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.

Hart (2001) highlights the potential for land converted to urban uses to be replaced with cropland expansion elsewhere. Specifically focusing on California, the leading agricultural state in the US, as well as the site of considerable urban sprawl over the past 50 years, he finds (p. 540):

> Many of the orchards, vineyards, and vegetable fields of 1949 have been paved over, to be sure, but new orchards, vineyards, and vegetable fields have been developed on land that once produced crops of lesser value, or no crops at all. It seems that the specialty crops produced in California can be grown-and, indeed, are grown-in other parts of the state and in other parts of the United States. The conversion of specialty cropland to urban uses is highly visible, because it occurs near the cities where the most people live and can see it. Far less visible are the farmers who have sold their land in these areas. They have taken their windfall profits and quietly invested them in replacement operations elsewhere that produce the same products.

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, p. 550) and the impact is currently being felt most strongly in developing countries. One of the most widely available metrics of biodiversity is the presence of bird species. Attempts to set aside lands for biodiversity and eco-system services in developing countries wrestling with the balance between economic and environmental amenities and the growing demand for ecosystem services and eco-tourism have proven controversial (Kristof 2010).

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. Jacobsen and Hanley (2009) offer a meta-analysis of studies specifically focusing on consumers' willingness to pay for biodiversity services. They find an Engel elasticity of 0.38 suggesting a modest, positive relationship between per capita income and the demand for biodiversity services. Kauppi et al. (2006) investigate the response of forest carbon to growth in per capita incomes and find that "no nation where annual per capita GDP exceeded $4,600" had a negative accumulation of forest carbon stock.

Recently there has been a surge of interest in Payments for Environmental Services (PES) by which those seeking to preserve biodiversity as well as carbon stocks. There are several successful examples of such payments in the Amazon (Anon. 2009), but in other regions (e.g., Indonesia), it seems that the payments required to prevent conversion to commercial use are often simply too high (Byerlee and Deininger 2010). 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 Organisation 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: Assessing the impact of climate change on agriculture is a daunting task which Alexandratos (2010, pp. 14-15) breaks down into four steps: (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) derive from (3) a way to shock models of the agricultural economy to determine changes in production, consumption, trade, etc. He notes that (4) must address changes in land and water constraints facing producers, as well as alternative adaptation strategies such as changing planting dates and introducing new crop varieties. Given the limited space available here, I will focus on step (3), with some attention to the implications for (4), and summarize some recent findings which bear of the question of agriculture’s capacity to attain the area and yield growth required to meet projected demands in 2050. However, the complexity of this entire chain of analysis is surely one of the key reasons why Alexandratos (2010) finds that studies apparently using the same assumptions generate widely different results.

Nelson et al. (2010, table 4) report estimates of climate change induced yield effects in 2050 based on two of the leading GCMs -- with and without the effects of CO2 fertilization. The latter is a potentially favourable, 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 neighborhood 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 global average yields, and somewhat larger area changes, suggest extremely 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[8] 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) has also addressed point (3) in the Alexandratos task list using a global, agro-economic crop modeling approach, albeit using different GCM inputs. He finds that, with CO2 fertilization present, but without adaptation, expected 2050 rainfed cereal yields fall by a nearly third in Southern Africa due to climate change as predicted by the Hadley GCM,

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[8] For wheat, the price rise is 111% over the 2050 baseline in response to a -7.6% yield shock (Δ_L^D), and 23.5% area reduction due to climate change effects under the NCAR-NoCF scenario, so that the estimated sum of elasticities is just 0.29. For rice these figures are 37% for the price rise, -10.2% for the yield shock, and 11.6% for the area change, so the ratio is 0.59. For maize the price rise is 52% in the face of -4.5% yield and 11.5% area shocks for a ratio of 0.31. Yield and area shocks were calculated based on information supplied by the authors.

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 CSIRO GCM and no-CO2 fertilization, with global prices rising by 10%. Using equation (2), this suggests that the sum of all three elasticities in the IIASA model may be about 0.5 for cereals taken as a group, which is consistent with the calculations reported above in the case of biofuels.

Deryng, Sacks, and N. Ramankutty (2009)have approached Alexandratos' step (3) in a simpler way, using a global scale crop simulation model and some stylized climate outcomes which are easier to interpret. They consider the impact of a 2°C rise in global temperatures – something in the range of possibilities for 2050 -- and find that the impact on global productivity is modest; however, the regional impacts are highly varied, with the tropics – and hence many developing countries – being hardest hit. Specifically, they find that average maize and soybean yields rise in high income countries, while falling slightly for wheat. The lowest income countries experience the sharpest yield losses, ranging from -13% for spring wheat to -22% for soybeans and -27% for maize.

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) have formalized the use of uncertainty analysis in a recent paper using econometrics in place of bio-physical crop growth models for (3); they estimate the impacts of climate change on agriculture in Sub-Sahara Africa in 2050 using panel data from the region. Schlenker and Lobell (2010) find that maize is most severely affected and millet the 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. Thus, while the impacts of climate change on global agricultural supplies in 2050 are expected to be modest in most studies, selected regional impacts may be much more severe. 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 a 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) focus on the United States and identify six types of mitigation opportunities in the agriculture and forestry sectors which they view largely as a "bridge to the future when new energy technologies come on board." These include: afforestation, biofuels, changes in management practices to reduce N2O and CH4 emissions, carbon intensive forest management, reduction of fossil fuel use in agriculture, and soil carbon sequestration. Of these options, afforestation and biofuel production are the main competitors for land, and these become the predominant source of mitigation between $15 and $30/tonne CO2eq. We have previously discussed biofuels as an additional source of demand for agricultural products; the focus here is on competition for agricultural land – and hence the supply side. This is an issue which Bruce McCarl has explored in some detail in the context of climate legislation being considered by the US Congress in the summer of 2009. 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.

Sohngen (2010) concludes forest carbon sequestration is likely to be an integral part of any global mitigation strategy as well. He 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. However, Seto et al. (2010, pp. 83-84) point out that any forest sequestration-based mitigation strategy has its limits. They undertake a thought experiment in which forest ecosystems are used as the sole vehicle to regulate global carbon emissions. They start with the 9 billion petagrams (Pg) of emissions and deduct the amount absorbed by current land and ocean sinks (5 Pg), leaving a net release of about 4 Pg C/yr into the atmosphere. Assuming a global forest carbon program, and an average rate of sequestration (2 – 3 tons C/sq km/yr), they estimate that the world would need to allocate 1 – 2 billion ha of land to additional forests in order to attain the necessary annual sequestration rate. This is an amount of land on the same order of magnitude as current cropland cover. And, within a century, when these forests are fully mature, sequestration will cease. Clearly forest sequestration must be viewed as one of a broader package of mitigation options.

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. Bruinsma (2009, table 10) estimates water requirements from irrigation to the year 2050. His calculations are at the country level, not the level of river basins; also his assessment of available water is based on physically available water, ignoring environmental, accessibilty and reliability critieria (more on this in a moment). Nonetheless, his calculations are instructive. He find the pressure on water resources to be highest in the Near East and North Africa and lowest in Sub Saharan Africa and Latin America. Globally, Bruinsma finds that irrigation water withdrawals in 2050 will be only 7% of renewable resource availability. However, this figure conceals great variation across countries. He finds that, in 2050, 13 countries are estimated to be consuming more than 40% of their renewable water resources for irrigation – considered to be a critical level, while another 10 countries will be above the 20% threshold. In South Asia, this ratio is expected to rise from 36% to 39% -- indicating great pressure of water resources.

A recent report by McKinsey & Co (2009), offers a more detailed assessment of the water puzzle for the year 2030, drawing heavily on the IFPRI water model (IFPRI, 2002) and taking account of non-agricultural demands as well. 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 may be slightly modified based on agricultural prices, it is by-and-large an independent phenomenon – and similarly with the demand for land for parks/biodiversity, as well as the impact of climate change on the suitability of land. However, there is also demonstrable potential for the supply of agricultural land to respond to scarcity in agricultural markets. Here, our focus turns to the elasticity of crop supply on the extensive margin, η_S^E. Despite the central importance of this parameter in the determination of long run agricultural land use, estimates of its value are spotty, particularly at the scale of continents, or indeed the globe, and particularly in the very long run.

As noted above, the elasticity of land supply with respect to commodity price is implicit in the results produced by the global economic models used for long run projections of agricultural supply and demand. And we can “back it out” of some of their reported findings. Consider, for example, the analysis by Fischer (2009) of the impact of climate change and biofuels growth on world agricultural markets. Under his most extreme scenario (Hadley A2, TAR-V1, without CO2 fertilization), aggregate crop output prices rise by 45% in 2050, relative to baseline (Table 9.1). This in turn induces a 58 mill ha increase in global cultivated land. Given a global cultivated area of 1727 Mha in the IIASA baseline, we obtain an arc-elasticity of supply response with respect to aggregated crop prices of 0.075.[9] 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 and 0.033, respectively in these two cases.[10]

These implied elasticities of land supply are similar 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. They compute the change in expected returns to land in various ways – each giving rise to a different implied elasticity. Their estimates range from 0.01 to 0.03. For Brazil, these same authors compute a much larger near term land supply elasticity (0.38 – 0.90).[11] This international variation in land supply response by region is also consistent with the work of Eickhout et al (2009) who estimate land supply functions based on an inventory of physical productivity of suitable land, by region. However, this approach, based on physical characteristics of the land does not take into account conversion costs which can be significant. Byerlee (personal communication) estimates that these costs amount to $1,000/ha in the Brazilian Cerrado, where land clearing and soil amendments are required, and $4,000 in

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[9] The arc elasticity is computed as follows: (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 which makes sense (as agricultural land expands, supply becomes more inelastic).

[10] See appendix for the associated equations. Note that these are total elasticities, not partial elasticities, as returns to land in other uses are not being held fixed in the model simulations. However, my assumption is that the main impact of biofuels and climate change (in his model) is on crop land returns.

[11] These authors also examine the responsiveness of total agricultural area (cropland and pasture land combined) in Brazil to land returns and find this to be very inelastic.

Indonesia for palm oil, where, in addition to land clearing and soil amendments, drainage is also required. Producers will only invest in such conversion if they see sustained demand for their products as has been the case with Brazilian soybean producers selling to the Asian market, as well as palm oil producers selling to the booming vegetable oils market, as well as for biodiesel. This suggests that the land supply response might be modest for small, or temporary price changes, but potentially quite large for sustained price increases over a period of a decade or more.

A recent study by the World Bank (2009) has suggested that similar area expansion is possible in Africa's Guinea Savannah Zone. Indeed, the title of this study--*Awakening Africa's Sleeping Giant* -- is indicative of their finding that this region, comprising 600 Mha of land, of which 400 Mha are suitable for agriculture and only about 40 Mha are currently cropped, offers opportunity for commercial agricultural development. It has agro-ecological features similar to the Cerrado of Brazil, which has been a source of tremendous growth in global oilseed production over the past two decades. However, effectively bringing this land into global markets will require more than simply clearing the land and modifying the soil. Agricultural policies must change, institutions must be strengthened and investments in infrastructure will be required (World Bank, 2009, p.2). These features go well beyond the simple representation of global land use in equation (1), but they do suggest that the long run global value for η_S^E may be considerably larger than authors assume in current model projections.

It is possible to move beyond speculation and back-of-the envelope calculations in the case of specific countries. Perhaps the most thorough examination of the response of cropland cover to changing economic returns is that of Lubowski, Plantinga, and Stavins (2006) who capitalize on two decades of National Resources Inventory data points in the United States to estimate the probability of land transitions from one state to another. These states include: cropland, conservation reserve, pasture, range land, forests and urban uses. By tracking changes in the land cover of each NRI data point and relating these transitions to land rental rates in each use, Lubowski, Plantinga, and Stavins (2006) are able to estimate how (e.g.) a rise in the relative returns to cropland affects the probability of cropland cover: (a) remaining in cropland, (b) transitioning to another state, or (c) being enhanced by transitions to cropland from other states. Ahmed, Hertel, and Lubowski (2008) have synthesized this econometric model into a set of reduced form elasticities of the sort discussed above. They estimate that the partial elasticity of US cropland supply in response to a perturbation in cropland rental is about 0.05 after 5 years and 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.

Lubowski's research focuses on private uses of *all* land cover types, and spans a period in which agricultural commodity prices were relatively low. By contrast, Sohngen and Brown (2006) focus more narrowly on the competition for land between crops and forestry (both public and private) and focus on those regions of the country where commercial forestry is most relevant. They supplement the NRI data set with forest inventory data which are available on an annual basis. Unlike Lubowski, Plantinga, and Stavins (2006); their unit of analysis is the county. And the estimated supply elasticities are much larger. While Sohngen and Brown (2006) do not report this in their paper, side calculations indicate that the elasticity of land supply to forestry in the Southern US ranges from 0.68 for natural pine forests to 5.55 for planted pine forests. The weighted average supply response for all forests is 1.48. (Note that these are all elasticitites with respect to land rents, and therefore considerably smaller than the associated value of η_S^E which refers to commodity price changes. Elasticities of supply of this magnitude from cropland to forestry suggest significant land supply responsiveness in the other direction as well.[12]

All of this suggests that there are likely very large differences between the short and long run elasticities of land supply to agriculture, and particularly to crops. Furthermore, it appears that those researchers undertaking long run analysis (say over 40 years time) may not fully recognize this large difference – placing excessive weight on the near term changes which can be readily observed in the data – such as the response of world markets to the 2007/2008 commodity price boom. By applying near term land supply elasticities in the context of long run analysis, economists will over-predict the price impacts of exogenous shocks such as climate change and biofuel policies, while also arriving at potentially misleading conclusions regarding global land use change in agriculture.[13]

VI. 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). Many of the authors reviewed in this paper have also suggested that there might be such a perfect storm, as the global farm and food system is 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 at the same

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[12] In separate work, Choi (2004) uses NRI data to estimate the supply elasticity of land to forestry in the context of a study of forest carbon sequestration in the Midwestern US using NRI data. He focuses on cross section variation. Calculations based on his model show a land supply elasticity with respect to land rents of 0.52.

[13] Whether they under-estimate or over-estimate the impact on land use change depends on the relative sizes of the mis-estimates, as shown in equation (1).

time 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 fueled by the rush on the part of foreign investors to invest in large scale developments of agricultural land in land abundant developing countries (Byerlee and Deininger 2010). This paper has sought to embed all of these changes in the context of a long run equilibrium system in which prices adjust to ensure that supply equals demand. This approach appears to offer some important insights into this important puzzle.

The problem with much of the existing analysis in this field is aptly summarized by Navin Ramankutty (personal communication) who summarized his experience at a recent conference on long run sustainability as follows:

> "Others at the conference asked our land resources group if we had enough land on the planet to grow the food required in the future. We replied that the answer depends on the diets people choose, but in principle, yes, given adequate water, the food could be grown. Focus then turned to the water group who thought carefully about this and suggested that, given sufficient energy for moving water from supply to demand nodes and desalinizing water, this should be possible. This brought in the energy sustainability group who suggested that energy availability in 2050 would depend critically on prices."

Clearly in order to understand the long run use of land in agriculture, we must treat this as a simultaneous system of biophysical relationships, economic behavior and market clearing conditions. That has been the theme of this paper – *the question is not whether sufficient land will be available for agriculture, but rather: What will be the long run price – both for land as well as for agricultural output and food?*

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 agricultural land use. Evidence presented in this paper from several of the most prominent 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 are able to replicate particular short run episodes 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 excessively on high frequency events, as they are more readily observed; however, this may lead to the omission of 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". Since land is, by definition, immobile, the supply-side of this story is inherently local in nature. Throughout this paper, as we have discussed the long run drivers of agricultural land use, we have seen that these vary spatially; whether discussing yield gaps, the use of land for biofuels or carbon sequestration, the impacts of climate change on agriculture, or the incidence of hypoxia related to fertilizer runoff, the impacts vary dramatically across locations. It is simply not possible to adequately evaluate the supply and demand for land by operating solely at continental or even national scales. Spatial resolution is essential. And the exciting thing is that 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 could be tremendous returns to public investments in open-source, publicly available 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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Technical Appendix to:

The Global Supply and Demand for Agricultural Land in 2050:

A Perfect Storm in the Making?

AAEA Presidential Address

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A simple model of long run demand and supply for agricultural land

The model developed in this appendix is the simplest possible framework for studying the six key factors shaping long run demand and supply for agricultural land. We begin with the demand for aggregate, agricultural output. The slope of this demand schedule is governed by the aggregate price elasticity of demand which captures the sales-weighted average responsiveness of all sources of demand to changes in the price of agricultural output, including food, fiber and food. This demand curve is subject to outward shifting over time due to exogenous growth in population, per capita income, and other factors, so that the *percentage change* in long run demand may be expressed as follows:

$$q_A^D = -\eta_A^D p_A + \Delta_A^D \qquad (1)$$

I postulate one global production function for agricultural output, which combines land (and water) with variable inputs (including labor, capital, fertilizer, etc.), wherein the latter are deemed to be in perfectly elastic supply in the long run. 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 in production (σ). Assuming constant returns to scale (clearly inappropriate at the farm level, but a good fit for industry behavior under entry and exit), zero pure economic profits (equation (3)), and cost minimizing behavior, this gives the derived demand for land in equation (2):

$$q_L^D = q_A^S - \sigma(p_L - p_A) - \Delta_L^D \qquad (2)$$

Here, q_L^D denotes the long run *percentage change* in global derived demand for land which is a function of three factors. Firstly, all else constant, boosting the supply of agricultural output, q_A^S, 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.

Note that aggregate output price (p_A) is just an index of input costs under the zero profits/constant returns to scale, so that the percentage change in this variable may be expressed as follows:

$$p_A = \sum_j \theta_j p_j \qquad (3)$$

Where p_j is the percentage change in the price of input *j*, and θ_j is the share of input *j* in total costs of agricultural production. Therefore, a scarcity of land will be indicated by a rise in the rental rate on land, relative to the composite price of inputs, which is just the price of output, i.e. $(p_L - p_A) > 0$. Under such circumstances, 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 described by σ. Note that I have also included the potential for exogenous "technological change" in the form of yield growth (expressed as a percentage of global average yields), Δ_L^D, which enters into this demand equation with a negative sign, such that faster "trend" 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.[14]

To complete the model, we must add equation (4) describing the long run supply of land to agriculture:

$$q_L^S = \nu_L^S p_L - \Delta_L^S \qquad (4)$$

As with aggregate demand, I include both a price-responsive element, indicating that additional land will be converted to agricultural uses if the relative return to land used in agriculture rises (based on the elasticity of land supply, ν_L^S), and an exogenous element, Δ_L^S, representing a shift in this land supply schedule owing to the conversion of agricultural land to other uses due to forces outside this simple model (e.g., urban sprawl).

The long run factor market closure for this model assumes that $p_j = 0, \forall j \neq L$. That is, long run prices for the variable factors of production are not affected by conditions within the agricultural sector. Applying this variable input price restriction into (3), and rearranging to isolate the change in land rents on the left hand side, yields a relationship whereby any long run change in agricultural prices is capitalized into land rents:

$$p_L = \theta_L^{-1} p_A \qquad (5)$$

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[14] I believe that in the very long run, even trend growth in yields is itself function of price. Consider the following thought experiment: What if the price of agricultural output were zero? Would be expect to see continued growth in yields? On the other hand, consider the huge investments made in R&D related to corn yields over the past few years as corn prices reached record levels. Clearly prices matter – particularly in the very long run.

Plugging equation (5) into the land supply equation (4), we obtain land supply in terms of commodity price:

$$q_L^S = \nu_L^S \theta_L^{-1} p_A - \Delta_L^S = \eta_A^{S,E} p_A - \Delta_L^S \qquad (6)$$

So we can see that the elasticity of land supply with respect to commodity price is likely to be considerably smaller than that the elasticity with respect to land rents. We will call this the *extensive margin* of supply response to commodity price: $\eta_A^{S,E} = \nu_L^S \theta_L^{-1}$.

Now rearrange (2) to isolate commodity supply on the left hand side. This becomes our agricultural commodity supply equation:

$$q_A^S = q_L^D + \sigma(p_L - p_A) + \Delta_L^D \qquad (7)$$

And substitute in equations (5) and (6) (recognizing that land supply must equal land demand in long run equilibrium), yielding:

$$q_A^S = \nu_L^S \theta_L^{-1} p_A - \Delta_L^S + \sigma(\theta_L^{-1} p_A - p_A) + \Delta_L^D \qquad (7)$$

Which we can rearrange to become:

$$q_A^S = [\nu_L^S \theta_L^{-1} + \sigma(\theta_L^{-1} - 1)] p_A - \Delta_L^S + \Delta_L^D \qquad (8)$$

The term in brackets [.] is the aggregate agricultural supply response to output price and is comprised of the extensive margin discussed above, and the intensive margin, $\eta_A^{S,I} = \sigma(\theta_L^{-1} - 1)$, which depends on the elasticity of substitution between variable inputs and land (larger σ gives a larger supply response) and the cost share of land (larger θ_L gives a smaller supply response). If land is the only input, then there is no scope for intensification. Therefore, the total supply response of agriculture, when measured in terms of responsiveness of output to output prices may be written as: $q_A^S / p_A = \eta_S^A = \eta_A^{S,I} + \eta_A^{S,E}$.

Equating commodity supply (8) to demand (1) yields:

$$(\eta_A^{S,I} + \eta_A^{S,E}) p_A - \Delta_L^S + \Delta_L^D = -\eta_A^D p_A + \Delta_A^D \tag{9}$$

Equation (9) may be solved for the long run, equilibrium commodity price change as a function of the exogenous shocks:

$$p_A^* = (\Delta_A^D + \Delta_L^S - \Delta_L^D) / (\eta_A^{S,I} + \eta_A^{S,E} + \eta_A^D) = \Delta / \eta \tag{10}$$

Equation (10) is extremely useful in understanding the commodity price impacts of exogenous shocks to commodity demand (e.g., due to biofuel mandates), to yields (e.g., due to climate change), or to land supply (e.g., due to urbanization). This relationship is mediated by the three key elasticities in our model: the intensive margin of supply response, the extensive margin, and the price elasticity of demand. For small values of these combined elasticities, we can expect to see very large price changes. As any one of these margins becomes more price responsive, we will see a rapid dampening of the commodity prices flowing from such shocks.

In order to deduce the implications for long run land use in agriculture, we plug (10) into (6) to obtain:

$$q_L^* = \eta_A^{S,E} \Delta / \eta - \Delta_L^S \tag{11}$$

Dividing top and bottom of the first term on the right hand side, we obtain the following expression for the long run equilibrium use of land in agriculture:

$$q_L^* = [(\Delta_A^D + \Delta_L^S - \Delta_L^D) / (1 + \eta_A^{S,I} / \eta_A^{S,E} + \eta_A^D / \eta_A^{S,E})] - \Delta_L^S \qquad (12)$$

Equation (12) shows the role of each of the six key determinants of the long run demand and supply for land in agriculture. These include three exogenous shifters: (i) shifts in commodity demand (e.g., due to biofuels or population growth), (ii) shifts in land supply (e.g., due to urbanization), (iii) exogenous growth in yields (e.g., due to prior investments in agricultural R&D), and three elasticities of supply and demand capturing the endogenous: (iv) potential for intensification of agriculture, (v) potential for agricultural land expansion, and (vi) potential for demand reduction.

From this expression, it can be seen that, if there is simultaneously no scope for intensification of production ($\eta_A^{S,I} = 0$) and no price responsiveness in demand ($\eta_A^D = 0$), then the denominator of the term in brackets [.] collapses to one and the land supply shocks cancel out. Therefore, any exogenous growth in net demand – for example due to a 5% increase in population relative to trend yields – gets fully translated into an equilibrium rise in land use in agriculture. As we will see, this is a pretty accurate characterization of much of the literature long run land use. All of the effort in these studies goes into computing the net demand factor, $(\Delta_A^D - \Delta_L^D)$, and, once that is done, the result is immediately translated into a change in agricultural land use, abstracting from the fact that such shocks might in fact lead to an *endogenous response* on the part of the farm and food system.

Equation (12) offers valuable insight into what is missed in such biophysical studies of global agricultural land use. In particular, note the role which the price responsiveness of yields and final demand play in this expression. By boosting the size of the denominator in (12), they serve as “shock-absorbers”, dampening the amount of land employed in agriculture over the long run in the face of positive net demand growth. That is, any outward shift in net demand tends to boost 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 (and indeed the long run activities of the agricultural research establishment) substituting variable inputs for land to achieve higher yields.

A second important insight from (12) 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 (this is the extensive margin of land use, and is captured by $\eta_A^{S,E}$). Indeed, if all three elasticities are equal, then the denominator of the bracketed term in (12) is just equal to three. In this case, each margin absorbs a third of the adjustment, and the equilibrium land use change is equal to the sum of one-third of the net demand growth, minus two-thirds of the agricultural land supply shock = 1/3 $(\Delta_A^D - \Delta_L^D)$ - 2/3 (Δ_L^S) .